The Astrophysical Journal, 532:L13–L16, 2000 March 20

SUPERWIND MODEL OF EXTENDED Lyα EMITTERS AT HIGH REDSHIFT

Yoshiaki Taniguchi and Yasuhiro Shioya
Astronomical Institute, Graduate School of Science, Tohoku University, Aramaki, Aoba, Sendai 980-8578, Japan
Received 1999 November 30; accepted 2000 January 28; published 2000 February 25

ABSTRACT

We propose a new model for the extended Lyα blobs found recently at high redshift ($z \sim 3$). The observational properties of these blobs are as follows: (1) the observed Lyα luminosities are $\sim 10^{43}\ h^{-2}$ ergs s^{-1}, (2) they appear elongated morphologically, (3) their sizes amount to ∼100 kpc, (4) the observed line widths amount to ∼1000 km s^{-1}, and (5) they are not associated with strong radio continuum sources. All these observational properties seem to be explained in terms of galactic winds driven by successive supernova explosions shortly after the initial burst of massive star formation in the galactic centers. The observed number density of Lyα blobs ($\sim 3.4 \times 10^{-5}\ h^3$ Mpc^{-3}) may be explained if their present-day counterparts are elliptical galaxies with a luminosity above $\sim 1L^*$.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: starburst — stars: formation

1. INTRODUCTION

1.1. *Surveys for High-Redshift Galaxies*

Recently, great progress has been made in observational astronomy by many astrophysicists; they have revealed that a large number of high-redshift galaxies can be accessible by the continuum emission of galaxies (the stellar continuum, the thermal continuum from dust grains, or the nonthermal continuum from plasma heated by supernovae) in a wide range of observed wavelengths between optical and radio (e.g., Williams et al. 1996; Lanzetta, Yahil, & Fernández-Soto 1996; Chen, Lanzetta, & Pascarelle 1999; Steidel et al. 1996a, 1996b; Dey et al. 1998; Spinrad et al. 1998; Weymann et al. 1998; van Breugel et al. 1999; Smail, Ivison, & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1999; Barger, Cowie, & Sanders 1999; Richards et al. 1999). On the other hand, it also has often been argued that galaxies forming at high redshift experience very luminous starbursts and thus could be much brighter in line emission, such as in Lyα and [O II] λ3727 emission lines (e.g., Partridge & Peebles 1967; Larson 1974; Meier 1976). However, although many attempts have been made to search for such very strong emission-line sources at high redshift (see Pritchet 1994 for a review; see also Pahre & Djorgovski 1995 and Thompson, Mannucci, & Beckwith 1996), most of these searches failed, except for some successful surveys around known high-z objects such as quasars (Hu & McMahon 1996; Hu, McMahon, & Egami 1996; Petitjean et al. 1996; Hu, McMahon, & Cowie 1999). Very recently, a new attempt with the Keck 10 m telescope has revealed the presence of Lyα emitters in blank fields at high redshift (Cowie & Hu 1998, hereafter CH98). Subsequently, Keel et al. (1999, hereafter K99) and Steidel et al. (2000, hereafter S00) also found a number of high-z Lyα emitters in other sky areas. Since these three surveys have reinforced the potential importance of searching for high-z Lyα emitters, now seems like the right time to investigate the origin of Lyα emitters.

1.2. *Extended Lyα Emitters at High Redshift*

A brief summary of the three recent surveys for high-z Lyα emitters (CH98, K99, and S00) is given in Table 1. In this Letter, we adopt an Einstein–de Sitter cosmology with a Hubble constant $H_0 = 100\ h$ km s^{-1} Mpc^{-1}. Each survey has discovered more than 10 strong Lyα emitters with the equivalent widths above 100 Å in the observed frame. It is interesting to note that five sources among them are observed to be very extended spatially, e.g., ∼100 kpc (K99; S00); we call them Lyα blobs (LABs) following S00. These five sources are cataloged as object 18, object 19, 53W002 (K99), blob 1, and blob 2 (S00). Their basic data are given in Table 2. Since the three LABs found in K99 are all strong C IV emitters (Pascarelle et al. 1996), it seems natural to conclude that they are photoionized by the central engines of active galactic nuclei (AGNs; K99). On the other hand, the remaining two LABs found by S00 have no evidence of an association with AGNs (S00). It should be also noted that their observed Lyα equivalent widths, EW(Lyα) ∼ 1500 Å, are much larger than those of the three K99 sources. These suggest that the origin of LABs may be heterogeneous, and thus the origin of S00 LABs is different from that of K99 ones.

Here we summarize the observational properties of the LABs found by S00 as follows: (1) the observed Lyα luminosities are $\sim 10^{43}\ h^{-2}$ ergs s^{-1}, (2) they appear elongated morphologically, (3) their sizes amount to $\sim 100\ h^{-1}$ kpc, (4) the observed line widths amount to ∼1000 km s^{-1}, and (5) they are not associated with strong radio continuum sources such as powerful radio galaxies. One possible explanation for their origin may be that these LABs are superwinds driven by the initial starburst in galaxies because a superwind could develop to a distance of ∼100 kpc in the low-density intergalactic medium (IGM) and because a superwind often blows with a biconical morphology (e.g., Heckman, Armus, & Miley 1990). In this Letter, we investigate this possibility. We also discuss a possible evolutionary link between LABs and high-z, dust-enshrouded submillimeter sources (Barger et al. 1999 and references therein).

2. SUPERWIND MODEL

2.1. *Superwinds from Forming Galaxies*

We consider the possibility that a LAB is a well-developed superwind seen from a nearly edge-on view. First, we investigate the properties of a superwind caused by the initial starburst in a galaxy. We adopt the dissipative collapse scenario for the formation of elliptical galaxies and bulges (i.e., the

TABLE 1
A Summary of the Three Lyα Emitter Surveys

Survey	Field[a]	z_c[b]	(z_{min}, z_{max})[c]	V[d]	EW_{lim}(Lyα)[e]	N(Lyα)[f]	N(LAB)[g]	n(LAB)[h]
CH98	HDF	3.4	(3.41, 3.47)	445	115	5	0	0
	SSA22	3.4	(3.41, 3.47)	445	90	7	0	0
K99	53W002	2.4	(2.32, 2.45)	8187	92	19	3[i]	3.66×10^{-4}
	HU Aqr	2.4	(2.32, 2.45)	8187	241	1	0	0
	NGC 6251	2.4	(2.32, 2.45)	8187	...	0	0	0
	53W002E	2.55	(2.49, 2.61)	7417	291	1	0	0
	53W002N	2.55	(2.49, 2.61)	7417	155	1	0	0
	53W002NE	2.55	(2.49, 2.61)	7417	184	4	0	0
S00	LBGS[j]	3.09	(3.07, 3.12)	1380	80	72	2	1.45×10^{-3}

[a] The name of the targeted field.
[b] The central redshift corresponding to the central wavelength of the narrowband filter (λ_c).
[c] The minimum and maximum redshift covered by the narrowband filter.
[d] The comoving volume covered by the survey in units of h^{-3} Mpc^3.
[e] The smallest equivalent width of the Lyα emission detected in the survey in angstrom units in the observed frame.
[f] The number of Lyα emitters found in the survey.
[g] The number of LABs found in the survey.
[h] The number density of LABs found in the survey in units of h^3 Mpc^{-3}.
[i] Associated with AGNs.
[j] The Lyman break galaxy spike region.

monolithic collapse model;[1] Larson 1974) together with the galactic wind model proposed by Arimoto & Yoshii (1987, hereafter AY87; see also Kodama & Arimoto 1997). In this scenario, the initial starburst occurs at the epoch of galaxy formation in the galaxy center. Subsequently, massive stars die and then a large number of supernovae appear. These supernovae could overlap and then evolve into a so-called superbubble. If the kinetic energy deposited into the surrounding gas overcomes the gravitational potential energy of the galaxy, the gas clouds are blown out into intergalactic space as a superwind (e.g., Heckman et al. 1990).

The evolution of such a superwind can be described by superbubble models (McCray & Snow 1979; Koo & McKee 1992a, 1992b; Heckman et al. 1996; Shull 1995). The radius and velocity of the shocked shells[2] at time t (in units of 10^8 yr) are then

$$r_{\rm shell} \sim 110 L_{\rm mech,\,43}^{1/5} n_{\rm H,\,-5}^{-1/5} t_8^{3/5}\ {\rm kpc} \tag{1}$$

and

$$v_{\rm shell} \sim 650 L_{\rm mech,\,43}^{1/5} n_{\rm H,\,-5}^{-1/5} t_8^{-2/5}\ {\rm km\ s^{-1}}, \tag{2}$$

where $L_{\rm mech}$ is the mechanical luminosity released collectively from the supernovae in the central starburst in units of 10^{43} ergs s^{-1}, and $n_{\rm H}$ is the average hydrogen number density of the IGM in units of 10^{-5} cm^{-3}.

We can estimate $L_{\rm mech}$ directly from AY87. For an elliptical galaxy with a stellar mass $M_{\rm stars} = 10^{11}\ M_\odot$, radius $r \simeq 10$ kpc, and $n_{\rm H} \sim 1$ cm^{-3} (Saito 1979; AY87), we expect $N_{\rm SN} \sim 3 \times 10^9$ stars that explode as supernovae. Since most of these massive stars were formed during the first 5×10^8 yr ($=t_{\rm GW}$, the epoch of galactic wind; AY87), we obtain $L_{\rm mech} \sim \eta E_{\rm SN} N_{\rm SN}/t_{\rm GW} \sim 10^{43}$ ergs s^{-1}, where $E_{\rm SN}$ is the total energy of a single supernova (10^{51} ergs) and η is the efficiency of the kinetic energy deposited into the ambient gas (∼0.1; Dyson & Williams 1980, p. 152). We assume, for simplicity, that a hydrogen number density in the IGM is $n_{\rm IGM}(z) \sim 0.1 n_{\rm cr}(z) = 0.1 n_{\rm cr}(0)(1+z)^3 \simeq 1.1 \times 10^{-6}\ h^{-2}(1+z)^3$, where $n_{\rm cr}(0)$ is the critical number density corresponding to the critical mass density of the universe, $\rho_{\rm cr}(0) = 3H_0^2/(8\pi G) \simeq 1.9 \times 10^{-29}\ h^2$ g cm^{-3}. We thus obtain $n_{\rm IGM}(3) \simeq 7.3 \times 10^{-5}\ h^{-2}$ cm^{-3} at $z = 3$. Since we assume that the superwind is seen from a nearly edge-on view, we obtain a characteristic size of the superwind of $l \sim 2r_{\rm shell} \sim 150$ kpc with $n_{\rm H,\,-5} = 7.3$. If we assume an opening angle $\theta_{\rm open} = 45°$ for the superwind (see § 2.3), we obtain an FWHM velocity of the superwind of $\sim 2v_{\rm shell} \sin\theta_{\rm open} \simeq 620$ km s^{-1}. These values appear consistent with the observations (S00).

2.2. *Frequency of Occurrence of Superwinds at High Redshift*

Since our superwind model implies that the most probable progenitors of LABs are forming elliptical galaxies, it is important to compare the observed number density of LABs at high redshift with that of elliptical galaxies in the local universe. The observed number density of LABs at high redshift can be related to the number density of elliptical galaxies responsible for the LABs $n_{\rm E\text{-}LAB}$ as

$$n_{\rm LAB} \sim n_{\rm E\text{-}LAB} \nu_{\rm SW} (1 - \Delta\Omega/4\pi), \tag{3}$$

where $\nu_{\rm SW}$ is the chance probability of finding superwinds in high-z elliptical galaxies and $\Delta\Omega$ is the full opening solid angle of a pair of superwinds in units of steradian. The last term is attributed to the assumption that we observe superwinds from a nearly edge-on view.

First, based on the results of CH98, K99, and S00, we estimate $n_{\rm LAB}$ using the following relation:

$$n_{\rm LAB} = \frac{N_{\rm LAB}({\rm CH98}) + N_{\rm LAB}({\rm K99}) + N_{\rm LAB}({\rm S00})}{V({\rm CH98}) f_{\rm cl}({\rm CH98}) + V({\rm K99}) f_{\rm cl}({\rm K99}) + V({\rm S00}) f_{\rm cl}({\rm S00})}, \tag{4}$$

where V is the comoving volume of the surveyed area (see

[1] It is not necessary to presume that this pregalactic cloud is a first-generation gigantic gas cloud. If a number of subgalactic gas clouds are assembled into one and then a starburst occurs in its central region, the physical situation seems to be nearly the same as that of the monolithic collapse.

[2] It is noted that the derivation of $r_{\rm shell}$ requires that the baryonic component dominate the gravitational potential. Although the presence of a dark matter halo requires that this estimate of $r_{\rm shell}$ not be valid at arbitrarily large radii, we do not take this effect into account because our discussion concerns a value of 1 order of magnitude.

TABLE 2
A SUMMARY OF THE FIVE Lyα BLOBS

Survey	Field[a]	Name[b]	z[c]	EW_{obs}(Lyα)[d]	F(Lyα)[e]	L(Lyα)[f]
K99 ……	53W002	53W002	2.390[g]	164	3.8×10^{-16}	3.9×10^{42}
	53W002	Object 18	2.393[g]	342	1.1×10^{-15}	1.1×10^{43}
	53W002	Object 19	2.397[g]	230	4.5×10^{-16}	4.6×10^{42}
S00 ……	LBGS	Blob 1	3.108	∼1500	1.4×10^{-15}	2.6×10^{43}
	LBGS	Blob 2	3.091	∼1500	1.2×10^{-15}	2.2×10^{43}

[a] The name of the targeted field.
[b] The name of the LAB.
[d] The observed redshift.
[d] The observed equivalent width of the Lyα emission in angstrom units.
[e] The observed Lyα flux in units of ergs cm^{-2} s^{-1}.
[g] The Lyα luminosity in units of h^{-2} ergs s^{-1}.
[g] Taken from Pascarelle et al. 1996.

Table 1) and f_{cl} is the clustering factor of galaxies in the surveyed volume with respect to the so-called field. In the CH survey, no LAB is found in the two blank fields; i.e., N_{LAB}(CH98) = 0 and f_{cl}(CH98) = 1. In the S00 survey, the two LABs are found in the protocluster region in which the number density of galaxies is higher by a factor of ≈6 than that in the field; i.e., N_{LAB}(S00) = 2 and f_{cl}(S00) = 6. In the K99 survey, although the three LABs are found in the 53W002 field, all of them are associated with AGNs. Therefore, we adopt N_{LAB}(K99) = 0. There is a rich group of galaxies in this field (Pascarelle et al. 1996). However, since it is difficult to estimate its clumping factor quantitatively, we assume f_{cl}(K99) ≃ f_{cl}(S00) = 6. We do not use the data of the other five fields surveyed by K99 because the detection limits of Lyα emission are higher by a factor of 2 than those of the other survey fields. Then we obtain $n_{LAB} \simeq 3.4 \times 10^{-5} h^3$ Mpc^{-3}.

Next, we estimate the probability of observing superwinds ν_{SW}. Since galaxies beyond $z \sim 5$ have been found (e.g., Hu et al. 1999; Dey et al. 1998; Spinrad et al. 1998; Weymann et al. 1998; van Breugel et al. 1999), we assume that elliptical galaxies were formed randomly at a redshift range between z = 10 and z = 3. According to the cosmology model adopted here, the above redshift interval corresponds to a duration of $\tau_{form} \approx 6.4 \times 10^8\ h^{-1}$ yr. For an elliptical galaxy with a mass of $10^{11}\ M_\odot$, the galactic wind breaks at t(SW) ≃ 3.5×10^8 yr after the onset of the initial starburst (AY87). Therefore, superwinds could be observed from such elliptical galaxies with $z \lesssim 6$. The chance probability of superwinds can be estimated as $\nu_{SW} = \tau_{SW}/\tau_{form}$, where τ_{SW} is the duration when a superwind can be observed as an emission-line nebula. As shown in § 2.1, a duration of $\tau_{SW} \approx 1 \times 10^8$ yr is necessary for developing the superwind to a radius of ∼100 h^{-1} kpc. Therefore, we obtain $\nu_{SW} \simeq 0.16\ h$.

Third, we estimate the probability of observing superwinds from a nearly edge-on view. A typical semiopening angle of superwinds may be $\theta_{open} \simeq 45°$ (e.g., Heckman et al. 1990; Ohyama, Taniguchi, & Terlevich 1997 and references therein). This gives $1 - \Delta\Omega/4\pi = \cos\theta_{open} \simeq 0.71$.

Then we obtain

$$n_{E\text{-}LAB} \sim n_{LAB}\nu_{SW}^{-1}(1 - \Delta\Omega/4\pi)^{-1} \sim 3.0 \times 10^{-4}\ h^2\ \mathrm{Mpc}^{-3}. \quad (5)$$

Integrating the luminosity function of elliptical galaxies derived by Marzke et al. (1994), we find that the above number density corresponds to that of elliptical galaxies above ≃1L* when h lies in a range between 0.5 and 1. Since the mass of an elliptical galaxy with L_* is ∼$10^{11}\ M_\odot$ (AY87; Kodama & Arimoto 1997), our superwind model appears consistent with the observations.

2.3. *Obscured Host Galaxies*

Finally, we comment on the visibility of galaxies hosting superwinds. In our superwind model, the central starburst region may be obscured by the surrounding gas and dust. Although AY87 assume that the superwind blows isotropically for simplicity, actual superwinds tend to have a biconical morphology. This implies that a lot of gas and dust may be located in the host galaxy with a disklike configuration that is responsible for the collimation of superwinds. These gas clouds are expected to absorb the radiation from the central star cluster if we observe superwinds from a nearly edge-on view. Let us consider a case in which gas clouds with a total mass of M_{gas} are uniformly distributed in a disk with a radius of r and a full height of d. We estimate the average number density of gas $n_H = M_{gas}/(\pi r^2 d m_H) \simeq 14 M_{gas,10} r_{10}^{-2} d_1^{-1}$ cm^{-3}, where $M_{gas,10}$ is in units of $10^{10}\ M_\odot$, r_{10} is in units of 10 kpc, d_1 is in units of 1 kpc, and m_H is the mass of a hydrogen atom. This gives an H I column density of $N_H = n_H r \simeq 4.2 \times 10^{23} M_{gas,10} r_{10}^{-1} d_1^{-1}$ atoms cm^{-2} for an edge-on view toward the gas disk, corresponding to the visual extinction of $A_V \sim 280$ mag for which we use the relation of A_V(mag) = $N_H/(1.54 \times 10^{21}$ cm^{-2}) (e.g., Black 1987). Even if the gas-to-dust mass ratio is 10 times smaller than that of our Galaxy, the visual extinction is still large, $A_V \sim 30$ mag. This may be responsible for the observed shortage of the ultraviolet luminosities accounting for the Lyα line luminosities (S00).

The obscuration described above may also be responsible for the observed large equivalent widths of the Lyα emission in S00; i.e., EW(Lyα) ∼ 1500 Å. Since these LABs are observed at $z \approx 3.1$ (see Table 2), the rest-frame equivalent widths are estimated to be EW^0(Lyα) ∼ 375 Å. This value is still larger by a factor of 2 than those expected for star-forming, dust-free galaxies, e.g., EW(Lyα) ≃ 50–200 Å (Charlot & Fall 1993; see also Tenorio-Tagle et al. 1999). However, in our model, strong continuum radiation from the central star cluster can be obscured by a lot of surrounding gas and dust. On the other hand, the Lyα emission arises from the superwind that is far from the host, e.g., $r \sim 100$ kpc. Therefore, the larger-than-normal EW(Lyα) is one of the important properties of our model.

2.4. *A Possible Evolutionary Link between LABs and Dust-enshrouded Submillimeter Sources*

As mentioned in § 2.2, the central starburst region in a forming elliptical galaxy could be enshrouded by a lot of gas with dust grains because these grains are expected to be supplied by either Population III objects (if any) or first massive stars in the initial starburst or both. Therefore, elliptical galaxies at this phase may be observed as dust-enshrouded (or dusty) submillimeter sources (DSSs). Subsequent supernova explosions blow out the gas into the IGM as a superwind $\sim 5 \times 10^8$ yr after the onset of the initial starburst. Elliptical galaxies at this superwind phase are assumed to be LABs in our model. We note that they are expected to be much fainter at submillimeter than the DSSs because a significant part of dust grains was already expelled from the galaxy. In summary, the dissipative-collapse formation of elliptical galaxies, together with the galactic wind model, suggests the following evolutionary sequence:

Step 1. The initial starburst occurs in the center of pregalactic gas cloud.

Step 2. This galaxy may be hidden by surrounding gas clouds for the first $\sim 5 \times 10^8$ yr (i.e., the DSS phase).

Step 3. The superwind blows and thus the DSS phase ceases. The superwind leads to the formation of extended emission-line regions around the galaxy (i.e., the LAB phase). This lasts for a duration of $\sim 1 \times 10^8$ yr.

Step 4. The galaxy evolves to an ordinary elliptical galaxy $\sim 10^9$ yr after the formation.

3. CONCLUDING REMARKS

The origin of Lyα emission from high-z objects may be heterogeneous, i.e., ionized gas irradiated by massive stars, ionized gas heated by superwinds, and ionized gas irradiated by the central engine of various types of AGNs. Such diversity is also reported for submillimeter-selected galaxies (i.e., DSSs) with $z > 1$ (Ivison et al. 2000). Therefore, in order to investigate the cosmic star formation history from high-z to the present day (e.g., Madau et al. 1996), we will have to study carefully what the observed Lyα emitters at high redshift are.

We would like to thank an anonymous referee for useful suggestions and comments. Y. S. is a JSPS fellow. This work was financially supported in part by the Ministry of Education, Science, and Culture (07044054, 10044052, and 10304013).

REFERENCES

Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23 (AY87)
Barger, A. J., Cowie, L. L., & Sanders, D. B. 1999, ApJ, 518, L5
Barger, A., Cowie, L. L., Sanders, D. B., Fulton, E., Taniguchi, Y., Sato, Y., Kawara, K., & Okuda, H. 1998, Nature, 394, 248
Black, J. H. 1987, in Spectroscopy of Astrophysical Plasmas, ed. A. Dalgarno & D. Layzer (Cambridge: Cambridge Univ. Press), 279
Charlot, S., & Fall, S. M. 1993, ApJ, 415, 580
Chen, H.-W., Lanzetta, K. M., & Pascarelle, S. 1999, Nature, 398, 586
Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319 (CH98)
Dey, A., Spinrad, H., Stern, D., Graham, J. R., & Chaffee, F. H. 1998, ApJ, 498, L93
Dyson, J. E., & Williams, D. A. 1980, Physics of Interstellar Matter (Manchester: Univ. Manchester Press)
Eales, S., Lilly, S., Gear, W., Dunne, L., Bond, J. R., Hammer, F., Le Fèvre, O., & Crampton, D. 1999, ApJ, 515, 518
Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Heckman, T. M., Dahlem, M., Eales, S. A., Fabbiano, G., & Weaver, K. 1996, ApJ, 457, 616
Hu, E. M., & McMahon, R. G. 1996, Nature, 382, 231
Hu, E. M., McMahon, R. G., & Cowie, L. L. 1999, ApJ, 522, L9
Hu, E. M., McMahon, R. G., & Egami, E. 1996, ApJ, 459, L53
Hughes, D., et al. 1998, Nature, 394, 241
Ivison, R. J., Smail, I., Barger, A. J., Kneib, J.-P., Blain, A. W., Owen, F. N., Kerr. T. H., & Cowie, L. L. 2000, MNRAS, in press (astro-ph/9911069)
Keel, W. C., Cohen, S. H., Windhorst, R. A., & Waddington, I. 1999, AJ, 118, 2547 (K99)
Kodama, T., & Arimoto, N. 1997, A&A, 320, 41
Koo, B.-C., & McKee, C. F. 1992a, ApJ, 388, 93
———. 1992b, ApJ, 388, 103
Lanzetta, K. M., Yahil, A., & Fernández-Soto, A. 1996, Nature, 381, 759
Larson, R. B. 1974, MNRAS, 169, 229
Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388
Marzke, R. O., Geller, M. J., Huchra, J. P., & Corwin, H. G., Jr. 1994, AJ, 108, 437
McCray, R., & Snow, T. P. 1979, ARA&A, 17, 213
Meier, D. L. 1976, ApJ, 207, 343
Ohyama, Y., Taniguchi, Y., & Terlevich, R. 1997, ApJ, 480, L9
Pahre, M. A., & Djorgovski, S. D. 1995, ApJ, 449, L1
Partridge, R. B., & Peebles, P. J. E. 1967, ApJ, 147, 868
Pascarelle, S. M., Windhorst, R. A., Keel, W. C., & Odewahn, S. C. 1996, Nature, 383, 45
Petitjean, P., Pécontal, E., Valls-Gabaud, D., & Charlot, S. 1996, Nature, 380, 411
Pritchet, C. J. 1994, PASP, 106, 1052
Richards, E. A., Fomalont, E. B., Kellermann, K. I., Windhorst, R. A., Partridge, R. B., Cowie, L. L., & Barger, A. J. 1999, ApJ, 526, L71
Saito, M. 1979, PASJ, 31, 181
Shull, M. J. 1995, in ASP Conf. Ser. 73, Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust, ed. M. R. Haas, J. A. Davidson, & E. F. Erickson (San Francisco: ASP), 365
Smail, I., Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, L5
Spinrad, H., Stern, D., Bunker, A., Dey, A., Lanzetta, K., Yahil, A., Pascarelle, S., & Fernández-Soto, A. 1998, AJ, 116, 2617
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, in press (astro-ph/9910144) (S00)
Steidel, C. C., Giavalisco, M., Dickinson, M., & Adelberger, K. L. 1996a, AJ, 112, 352
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996b, ApJ, 462, L17
Tenorio-Tagle, G., Silich, S. A., Kunth, D., Terlevich, E., & Terlevich, R. 1999, MNRAS, 309, 332
Thompson, D., Mannucci, F., & Beckwith, S. V. W. 1996, AJ, 112, 1794
van Breugel, W. J. M., de Breuck, C., Stanford, S. A., Stern, D., Rottgering, H., & Miley, G. 1999, ApJ, 518, L61
Weymann, R. J., Stern, D., Bunker, A., Spinrad, H., Chafee, F. H., Thompson, R. I., & Storrie-Lomberdu, L. J. 1998, ApJ, 505, L95
Williams, R. E., et al. 1996, AJ, 112, 1335