# SEARCHES FOR PRIMEVAL GALAXIES

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ABSTRACT. We review primeval galaxy searches based on the Ly$\alpha$ line emission. Simple arguments are given which suggest that primeval galaxies (interpreted here as ellipticals and bulges undergoing their first major bursts of star formation) should be detectable with present-day technology. Many active objects are now known at large redshifts, which may be plausibly interpreted as young galaxies, but there is so far no convincing detection of a field population of forming normal galaxies. This suggests that either primeval galaxies were obscured, and/or are to be found at higher redshifts, $z_{gf} > 5$.

Galaxy formation is one of the central problems of modern cosmology. It touches on many different subfields of astrophysics: formation and evolution of large-scale structure, chemical evolution and star formation history of galaxies and stellar populations, physics of star formation, etc. Discovery of normal galaxies forming at large redshifts will be an important milestone and would open many new exciting problems and fields of inquiry.

The purpose of this review is to describe some of the observational issues involved, to describe the results from modern searches for primeval galaxies (hereafter PGs), and the future prospects. Previous reviews include those by Davis 1980, Koo 1986, Spinrad 1987, 1989, Cowie 1988, 1989, Djorgovski 1988a,b, 1992, and numerous excellent papers in the proceedings edited by Frenk et al. 1989 and Bergeron et al. 1988; and also in Hewitt et al. 1987, Thuan et al. 1988, Kron & Renzini 1988, Kron 1990, and many others.

Many different things are meant by galaxy formation. At least two distinct kinds of phenomena are involved (Silk & Norman 1981; Silk 1987; Larson 1990; etc.): (1) assembling of the mass in galaxy-size units, e.g., via merging; and (2) conversion of gas into stars, and energy dissipation. They may, but need not coincide in time or in the location; neither need have had a well defined or even a unique peak epoch. The first is the purview of theories and numerical simulations. Unfortunatelly, since most of the mass is (and probably always was) dark, direct observations of (1) are difficult or impossible. The second is what may be observable, and is where most of the energy release probably occurs. It is perhaps better to think of galaxy formation not as a single, well defined event or phenomenon, but rather as an evolving sequence of processes, which continue to the present epoch. There is no sharp or natural boundary between galaxy formation and galaxy evolution.

Some galaxy formation clearly happens even today. First, star formation in the disks of most normal spiral galaxies has not changed very substantially over the Hubble time, and for the late types it may even be on the rise. This continuing star formation may be powered by a gradual infall of gas. A better term for it would be galaxy *growth*. There may be genuine young *dwarf* galaxies at $z \sim 0$, such as I Zw 18 (Kunth & Sargent 1986), or H I 1225+018 (Giovanelli & Haynes 1989). It is still not clear whether such systems are just begining their first major bursts of star formation, or whether they represent rejuvenated old dwarfs, and how many progenitors of such systems (i.e., large intergalactic gas clouds) there may be left at $z \sim 0$. In any case, such objects are rare, judging by the failure of many searches to find more of them. Whereas these may be true young galaxies, they



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are probably distinct from the high-$z$ progenitors of normal galaxies, and contain only a small fraction of the total baryonic mass. Finally, there are merger remnants and merger-stimulated starburst galaxies, including many ultraluminous IRAS objects, in which large star formation rates ($\sim 100\ M_{\odot}$/yr) are implied. Had any of them been discovered at large redshifts, they could have been readily called PGs. However, it is clear that at $z \sim 0$ these are mergers of preexisting galaxies, and as such, they are better called examples of galaxy *trans*formation, than a formation proper. For the purposes of this review, we define PGs as the progenitors of normal ellipticals and bulges, undergoing their first major bursts of star formation at large redshifts, a definition assumed by many observers.

The exceptional smoothness of the CMBR photosphere at $z \sim 1000$ ($\Delta T/T < 10^{-5}$ on galaxy and cluster scales, as of this writing) places an upper limit on the redshift of galaxy and large-scale structure formation. The absence of an obvious population of PGs at $z < 1$ places a lower limit to the characteristic redshift of galaxy formation, $z_{gf}$. We now know normal galaxies and rich clusters out to $z \sim 1$ (Gunn et al. 1986; Thompson & Djorgovski 1991), radio galaxies out to $z = 3.8$ (Chambers et al. 1990), and quasars out to $z = 4.9$ (Schneider et al. 1991). The redshift range $\sim 5 - 1000$ is still a *terra incognita*, in which the bulk of galaxy formation may have happened, or at least began.

Peebles 1989 lists several simple, general arguments which suggest that $z_{gf} \sim 10 \times 3^{\pm 1}$. The basic idea is that several lines of reasoning and evidence suggest that protogalaxies collapsed by about a factor of 10, which would make galactic halos adjacent at $z \sim 10$. On the other hand, most n-body models of hierarchical structure formation, and the CDM scenario in particular, suggest that galaxy formation happens late, i.e., $z_{gf} \simeq 2 \pm 1$ (e.g., Baron & White 1987; Silk & Szalay 1987; White 1989; etc.). What these models really predict is the peak merging epoch, which is then identified with the epoch of galaxy formation, which is reasonable, since merging of gas-rich protogalactic fragments may be the cause of the initial starbursts. A good argument for a higher $z_{gf}$ may be the existence of copious quasars and radio galaxies at $z > 3$, and the absence of a sharp (if any) quasar number density cutoff out to $z \sim 5$. In order to form quasars at $z > 4$, it may be necessary to start formation of their host galaxies at $z > 10$ or beyond (Turner 1991). A reasonable upper bound on $z_{gf}$ may be given by the requirement that protogalaxies are able to cool via the inverse Compton mechanism on the CMBR photons, which is ineffective at $z > 30$ or so. The plausible hunting ground for PGs is then at $2 < z < 30$. Most searches for PGs to date have concentrated to lower redshifts, $z < 5 - 7$, mainly because of technical limitations: beyond that, Ly$\alpha$-bright objects become hard to observe in the visible light.

Fossil evidence about the star formation histories of normal galaxies is written in their color distributions at $z \sim 0$. For all age-sensitive colors, e.g., $(U - B)$ or $(B - V)$, the distributions are bimodal, with a broad blue peak corresponding to disks and irregulars, and a narrow red peak corresponding to ellipticals and bulges. For most stellar population synthesis models, these correspond roughly to the average stellar ages of $\sim 3 - 6$ Gyr and $\sim 8 - 20$ Gyr. For a reasonable range of cosmologies, these translate to the characteristic star formation redshifts of $\sim 1 - 3$ for disks, and $\sim 5 - 30$ for ellipticals and bulges. Copious faint blue galaxies seen in deep surveys, such as those by Tyson 1988, Cowie et al. 1988, or Lilly et al. 1991, are thought to be largely at $z < 3$, due to the absence of a Lyman limit break in their broad-band colors (Guhathakurta et al. 1990). Possibly, these optically faintest galaxies seen so far are disks and dwarfs undergoing some luminosity evolution at $z \sim 0.5 - 3$. The absence of any $z > 1$ galaxies in the spectroscopic surveys reaching down to $B \sim 22^m$ also suggests that we haven't yet seen a population of young ellipticals or bulges. Since the average stars in ellipticals and bulges are older than the average stars in disks, it follows that ellipticals and bulges probably form at $z > 3$.

Faint galaxy counts also provide a means of estimating the expected number density of PGs on the sky. There are about $10^6$ galaxies/degree$^2$ down to $m \sim 27$, which can only be a lower limit on their total surface density: fainter objects probably exist, and many galaxies may also be obscured. Appeals to merging are unlikely to change these estimates by a large factor, since most galaxies today have disks which are dynamically fragile, and at least a half of the Hubble time old. If a galaxy spends at least a percent of its lifetime in a PG phase, then there should be at least $\sim 10^4$ PGs per degree$^2$, or about one every half arcmin. An alternative estimate may be made as follows: Integrating the comoving volume per solid angle for $z > 5$, say, gives $\sim 1 - 10$ Mpc$^3$/arcsec$^2$, depending on the cosmology. At $z \sim 0$, there are a few $\times 10^{-3}$ $L_*$ galaxies/Mpc$^3$. Again assuming a negligible density evolution, we derive $\sim 10^{-2}$ PGs per arcsec$^2$, or about one every 10 arcsec, close to our previous estimate. There are thus enough PGs on the sky, with the r.m.s. well matched to the fields of our detectors. It is also possible that PGs are strongly clustered: in just about all reasonable scenarios for structure formation, the highest peaks of the density field collapse first, and such peaks should be highly correlated. With this in mind, we started a search for protoclusters around $z > 4$ quasars (Djorgovski et al. 1992).

There are three principal energy release mechanisms from forming galaxies. First, there is the binding energy, which must be released as a protogalaxy cools and collapses. If this process occurs at $z > 20$ or so, the dominant mechanism is the inverse Compton cooling on the CMBR, which in principle may be observable today as a distortion of the CMBR spectrum. Energy from dissipative shocks in collapsing protogalaxies may also be released in recombination lines, such as Ly$\alpha$. Taking an average galaxy mass of $\sim 10^{45}$ g, and an average 1-D internal velocity of $\langle V^2 \rangle \sim (200$ km/s$)^2$, we get $E_{bind} \sim 10^{59}$ erg for a typical non-dwarf galaxy. A comparable amount of binding energy must also be released from collapsing protostars, but the form of its release depends very much on the physical state and chemical composition of the early ISM. The dominant energy source, at least for normal galaxies, is the nuclear burning in stars: $E_{nuc} \sim M_\star c^2 \Delta X \epsilon$, where $M_\star \sim 10^{43}$ g is the total baryonic mass consumed in the primordial starburst, $\Delta X = \Delta Z + \Delta Y \sim 0.05$ is the fraction of hydrogen converted into the heavier elements, and $\epsilon \sim 1$ Mev / 1 Gev = 0.001 is the net efficiency of the nuclear reactions. This gives $E_{nuc} \sim 10^{61}$ erg for a typical elliptical or a massive bulge. Finally, a young galaxy may develop an active nucleus, e.g., quasars at $z > 4$. For a characteristic AGN luminosity of $\sim 10^{45}$ erg/s $\sim 10^{12} L_\odot$, and a lifetime $\tau \sim 10^8$ yr, we get $E_{AGN} \sim 10^{60}$ erg, some fraction of which may be coupled to the gas within the host protogalaxy. Depending on the as yet poorly understood feedback processes in protogalaxies, these characteristic energies may be related to the characteristic masses or other global properties of galaxies (cf. Ikeuchi & Norman 1991).

The observationally relevant quantity is not the total released energy, but the luminosity, i.e., $L \sim E/$(time scale). There are roughly three relevant time scales: the free fall or a typical starburst duration time scale, $t_{ff} \sim t_\star \sim 10^7 - 10^8$ yr; a cluster crossing or a merging time scale, $t_{merg} \sim 10^9$ yr; and a time scale for a gradual infall over the Hubble time, $t_{inf} \sim 10^{10}$ yr. Dividing the characteristic energy of $\sim 10^{61}$ erg by these time scales, we derive the corresponding luminosities of $\sim 10^{12}$, $10^{11}$, and $10^{10}$ $L_\odot$. The first one corresponds roughly to typical quasar luminosities, and such PGs, if they existed and were not confused with quasars (Meier 1976; Terlevich, this volume) presumably would have been detected by now. Formation of a large fraction of old stars over a time period as short as a single $t_{ff}$ requires a remarkable synchronicity, and may be unlikely. The intermediate time scale (formation over a Gyr) looks physically more appealing, especially if vigorous merging of protogalactic fragments is involved, as is suggested by n-body simulations. The last time scale gives the luminosities comparable with those of normal galactic disks.

The absolute magnitudes corresponding to these luminosities are $M \sim -26$, $-23$, and $-20$. At the redshifts of interest, the distance moduli are $(m - M) \sim 47 \pm 3$, depending on the cosmology. Therefore, we may expect unobscured protoellipticals to have apparent magnitudes roughly $\sim 24 \pm 3$, which is not strongly dependent on the wavelength, since the UV continua of actively star-forming galaxies are fairly flat. This is well within our observational abilities in the optical, and, at the bright end, in the near-IR as well. We note also that at $z \sim 2 \pm 1$, the expected magnitudes of disk galaxies with $M \sim -20$ are roughly $m \sim 26 \pm 2$, comparable with those of the faint blue galaxies seen in deep field surveys.

The key issue of observability of PGs is whether they are dusty or not. If the primordial starbursts were completely shrouded, the energy would emerge at $\lambda_{rest} \sim 30 - 100 \mu$m, and would be observable in the FIR/sub-mm region today. If they were unobscured, the bulk of the energy would be emitted in the restframe UV, and be observable today in the optical or NIR region. This choice determines the observing strategy.

There is a methodological choice of either searching for individual sources, or trying to detect collective effects of forming galaxies, such as diffuse backgrounds. Depending on the importance of dust, PGs could be sources of a detectable UV/optical/NIR background, or a FIR/sub-mm background (recall the vigorous activity which followed the claim of a sub-mm excess in the CMBR by the Nagoya-Berkeley collaboration), and could also contribute substantially to at least some parts of the x-ray background. Discussions of these issues can be found, e.g., in papers by Songaila et al. 1990, Djorgovski & Weir 1990, and numerous good reviews in the proceedings edited by Bowyer & Leinert 1990.

Whereas the energetics does not seem to pose a major problem in detecting PGs, there is still a problem of their recognition. One needs some sort of a spectral signature of young, actively star-forming galaxies at large redshifts. Except for the Lyman break at 912 Å, their continua should be relatively featureless and flat, thus containing little redshift information. So far, broad band color selection in deep surveys never produced any good PG candidates. (An equivalent problem exists if one wishes to search for obscured primeval galaxies at FIR or sub-mm wavelengths.) We are driven to search for emission line signatures, e.g., strong recombination lines such as Ly$\alpha$. Ly$\alpha$ emission in PGs can be powered by photoionization by young, massive stars (they must be present, since there are metallic lines in high-$z$ quasars, and most of the mass in old stellar populations at $z \sim 0$ is metal rich). Additional mechanisms include shock ionization from infalling and colliding protogalactic fragments, supernovæ(Shull & Silk 1979), cooling of the first stars (Silk 1977, 1985), and photoionization by early AGN, if any are present. Using the semiempirical conversion between the SFR and H$\alpha$ luminosity by Kennicutt 1983, and the simple case-B photoionization models to convert to Ly$\alpha$, we estimate the Ly$\alpha$ luminosity of $\sim 10^{42}$ erg/s for each $1 M_\odot$/yr of star formation with a normal IMF (an IMF biased towards the high-mass end would be of course more effective). The characteristic SFR in PGs is estimated at $\sim 10^{2\pm1} M_\odot$/yr, giving expected $L(\mathrm{Ly}\alpha) \sim 10^{44\pm1}$ erg/s. At the characteristic luminosity distance of $\sim 10^{29}$ cm, corresponding to $(m - M) \sim 47$, the expected Ly$\alpha$ line fluxes are $\sim 10^{-16\pm1}$ erg/cm$^2$/s, which is observable with present-day technology.

There are indeed many Ly$\alpha$ galaxies at high redshifts now known. However, essentially all of them are associated in some way with active nuclei: powerful radio sources (e.g., 3C 326.1 at $z = 1.825$; McCarthy et al. 1987), companions of high-$z$ quasars (e.g., PKS 1614+051 at $z = 3.215$; Djorgovski et al. 1985, 1987), etc. Discussions and further references have been given in the reviews by Spinrad 1987, 1989 and Djorgovski 1988a,b. Since then, more interesting objects have been discovered. Among the radio galaxies are 3C 294 at $z = 1.786$ (McCarthy et al. 1990), 3C 257 at $z = 2.474$ (Dickinson et al., in prep.), B2 0902+34 at $z = 3.395$ (Lilly 1988), and 4C 41.17 at $z = 3.800$ (Chambers et al. 1990), and several others. These objects are characterized by a strong, extended ($\sim 100$ kpc) Ly$\alpha$ emission, sometimes with a very low ionization (suggesting that at least some fraction of the line emission is due to photoionization by young stars), and a clumpy, low surface brightness continuum morphology. These may be genuine forming galaxies, but the presence of powerful radio sources in them makes them suspect. Heckman et al. 1991 and Hu et al. 1991 discovered extended Ly$\alpha$ nebulosities or possible galaxy companions near several high-$z$ radio loud quasars. Another interesting new quasar companion, C1548+0917, has been found by Steidel et al. 1991. There is at least one detection of Ly$\alpha$ emission from a damped Ly$\alpha$ absorber (towards H0836+113, at $z = 2.466$, by Wolfe et al. 1991). Lowenthal et al. 1991 discovered an active galaxy near a damped absorber at $z = 2.309$ towards the quasar PHL 957. (Another possible case at $z = 3.409$, found by Turnshek et al. 1991 still needs a confirmation.) Finally, a high-ionization emission line galaxy at $z = 2.286$, apparently associated with the IRAS FPS 10214+4724 was found by Rowan-Robinson et al. 1991. This object (or possibly a hidden companion thereof) has an estimated luminosity of $\sim 10^{14} L_\odot$; it may well be an obscured quasar, rather than an ultrapowerful starburst.

These discoveries are encouraging, and demonstrate that Ly$\alpha$-luminous objects with properties which may be expected of PGs can be found with the existing technology today. Some or all of them may well *be* PGs, albeit containing active nuclei. However, it would be much better if a population of field objects, not associated in any way with active nuclei, was found at comparable or higher redshifts.

Emission-line based PG searches cover a parameter space whose axes are: (1) the redshift coverage, $\Delta z$; (2) the depth or limiting flux, $F_{lim}$; and (3) the solid angle coverage, $\Delta\omega$. The plane defined by ($\Delta z$,$F_{lim}$) describes the star formation history; the plane defined by ($F_{lim}$,$\Delta\omega$) reflects the evolution of the luminosity function; and the plane defined by ($\Delta z$,$\Delta\omega$) is sensitive to the cosmology. Observing strategies can be designed on the basis of perceived coverage of the most relevant or the least explored portions of this parameter space. For example, slitless spectroscopy surveys, such as the grism surveys by Koo & Kron 1980 and Schmidt et al. 1986 cover a large $\Delta\omega$, and may have a large $\Delta z$, but are not very deep; spectroscopic long-slit surveys cover a small $\Delta\omega$, can be very deep, and with a good $\Delta z$; and narrow-band imaging surveys, be it with interference filters or with a Fabry-Perot, cover an intermediate $\Delta\omega$, go very deep, but have only a limited $\Delta z$. The surveys to date have concentrated on the Ly$\alpha$ line; in the future, equivalent surveys may be done in the IR, searching for the Balmer or oxygen lines ($\lambda$ 3727 and 5007 Å), or even Ly$\alpha$ itself at $z > 10$.

Surveys prior to 1985 have been reviewed by Koo 1986. Several field surveys have been conducted since then. Particularly noteworthy are the narrow-band imaging surveys by Pritchet & Hartwick 1987, 1990, the narrow-band and long-slit surveys reported by Cowie 1988, and the long-slit survey by Lowenthal et al. 1990. Djorgovski et al. (in prep.) obtained deep, narrow-band images centered on the redshifted Ly$\alpha$ line of about 40 fields of quasars at $z \sim 1.9 - 3.8$. The fields were searched for objects showing Ly$\alpha$ emission in the bands with typical $\Delta z \sim 0.01$. No obvious candidates were found down to the typical $F_{lim} \sim 1.5 \times 10^{-17}$ erg/cm$^2$/s, although some very faint, possible line-excess objects were detected. We use the limits from these surveys, the earlier work referenced by Koo 1986, and the results to date from our own surveys, described below, in Figures 1 – 3.

Our first experiment (Thompson et al. 1990, 1992a,b) consists of deep imaging of selected fields in a series of adjacent narrow bands, with a spectroscopic follow-up of all objects which show a probable line emission excess in one or more bands. A special, low-resolution Fabry-Perot imaging interferometer was built for this purpose. Several high-latitude fields, which transit close to the zenith at Palomar, with minimal IRAS cirrus, away from bright stars, galaxies, known foreground clusters, and as "empty" as possible, were selected. The field of view is $\sim$ 5.5 arcmin square. Three-dimensional data cubes are built up by successive exposures stepped in wavelength an amount equal to the instrumental FWHM ($\simeq 10^3$ km/s in the restframe for Ly$\alpha$, or $\sim 20 - 25$ Å). We search in several redshift intervals chosen to avoid the night sky emission lines: 2.80 – 2.89, 3.27 – 3.45, 4.42 – 4.61, and 4.74 – 4.90. Data cubes corresponding to these redshift slices are obtained and searched for objects which show a possible emission line "excess". To date we have surveyed 3 fields (0.03 deg$^2$) in the $\Delta z$ range 4.42 – 4.61, and 6 fields (0.06 deg$^2$) in the range 4.74 – 4.90, down to the limit of $AB_\nu \sim 23^m$. This corresponds to a surface density of $< 13$ objects/deg$^2$ down to $F_{lim}(\mathrm{Ly}\alpha) \sim 10^{-16}$ erg/cm$^2$/s, declining to a surface density of $< 2600$ objects/deg$^2$ down to $F_{lim}(\mathrm{Ly}\alpha) \sim 3.2 \times 10^{-17}$ erg/cm$^2$/s, for compact objects ($\leq 2$ arcsec); for extended objects, the limits are less stringent (about a factor of two worse). The net surveyed comoving volume so far is $1.41 \times 10^5 h_{75}^{-3}$ Mpc$^3$ for $\Omega_0 = 0$, or $2.14 \times 10^4 h_{75}^{-3}$ Mpc$^3$ for $\Omega_0 = 1$. In a typical data cube, we find 3 or 4 excellent candidates, and up to 20 or more other faint emission line galaxies worth following up. So far we confirmed spectroscopically half a dozen starburst galaxies at intermediate redshifts, typically $z \sim 0.4 - 0.9$ (detected through their [O II] or [O III] emission), and a couple of low-$z$ AGN. There are several intriguing faint objects where long-slit spectra have confirmed the reality of the faint line emission detected by the Fabry-Perot, but with a signal insufficient to determine the redshifts unambiguously. Some of them may be genuine young, star-forming Ly$\alpha$ galaxies, but more data are needed before we can be certain of their nature. If none of them are actually primeval galaxies, our preliminary limits may already be in conflict with the CDM model predictions by Baron & White 1987 (see Figure 1).

Our second experiment is a serendipitous long-slit spectroscopic search, using data obtained in the course of other projects. After two-dimensional sky subtraction, the spectroscopic CCD frames are examined carefully for any possible emission-line objects which may have been covered by the slit. We typically span the wavelengths 4000 – 8000 Å, corresponding to a Ly$\alpha$ redshift of 2.3 – 5.6. One-hour exposures reach $F_{lim}$ comparable to the Fabry–Perot survey, depending in wavelength on the night sky spectrum. These exposures have a large, continuous redshift coverage, but they cover a much smaller area, typicaly $\sim$ 2 arcsec by 2 arcmin. To date, $\sim$ 50 long exposures have been examined, and we anticipate that several tens more will be covered in this search within a year or two. So far, at least a dozen interesting objects were found. They are mostly star forming or mildly active galaxies at moderate redshifts. Typical magnitudes are in the range $19^m - 23^m$, and redshifts in the range $z \sim 0.3 - 0.8$, with the median $z \simeq 0.6$. The most distant object found so far is an apparently normal $\sim 24^m$ field galaxy, G0333+3208, at $z = 1.018$ (Thompson & Djorgovski 1991). Optical luminosities and [O II] emission equivalent widths of these objects are consistent with those of $\sim L_*$ galaxies undergoing a relatively mild evolution, powered by star formation. Their optical continuum shapes are broadly similar to those of the numerous, faint blue or flat-spectrum galaxies found in deep field surveys.

Figures 1 – 3 illustrate the limits on the Ly$\alpha$ PGs from various modern surveys, assuming that none of the the faint candidates found so far are PGs, and not counting various active objects found at $z \sim 2 - 5$. We used a Friedman cosmology with $H_0 = 75$ km/s/Mpc and $\Omega_0 = 0.2$ in computing the distance-dependent quantities and models, but the results are not very sensitive on that choice of parameters, at least at the level of

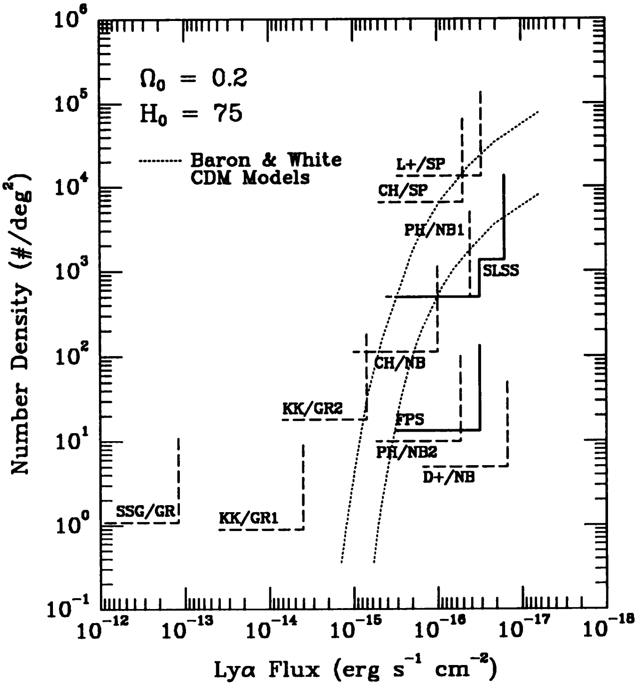


**Figure 1.** Limits on the surface number density of Ly$\alpha$ PGs, as a function of the limiting line flux. The limits are labeled as reference/method: KK = Koo & Kron 1980; SSG = Schmidt et al. 1986; PH = Pritchet & Hartwick 1987, 1990; CH = Cowie & Hu, rep. in Cowie 1988; L+ = Lowenthal et al. 1990; D+ = Djorgovski et al., in prep.; FPS = our Fabry-Perot survey; SLSS = our serendipitous long-slit survey; GR = grism (slitless spectroscopy); NB = narrow-band imaging; SP = spectroscopy. The limits shown are schematic, since the actual lines may be curved, reflecting a spread in sensitivity for a given survey. The dotted lines indicate the range of CDM-based models from Baron & White 1987, scaled for the $H_0 = 75$ km/s/Mpc, $\Omega_0 = 0.2$ cosmology. This diagram does not indicate the redshift coverage for each survey.

precision of the data. The limits were taken or computed on the basis of quoted papers, and uncertainties of the order of a factor of 2 may be typical. The limits reached in several independent modern surveys are such that normal forming galaxies, or at least E's and bulges, should have been found, if they existed at these redshifts, and were unobscured.

Possibly the most likely explanation for their absence is that PGs were dusty (see, e.g., van den Bergh 1990). If the restframe extinction was higher than $A_V \sim 1^m$, flux at 1216 Å would be depressed by more than a factor of 10. Several pieces of evidence support this hypothesis, but none of them is compelling, and for each one there are about equally good (or bad) counterarguments. First, it can be argued *a priori* that since the luminous starbursts seen at low redshifts are very dusty, so should their high-$z$ counterparts. On the other hand, it is not obvious that the physical conditions in protogalaxies were sufficiently similar for this analogy to work; for example, the *first* stars must have formed in an environment without dust grains. Second, Ly$\alpha$ emission from low-$z$ star-forming dwarfs is generally very weak, although some exceptions do exist (Meier & Terlevich 1981; Deharveng et al. 1985; Hartman et al. 1988). The observed Ly$\alpha$/H$\beta$ ratio in dwarfs appears to be a strong function of metallicity, suggesting that possibly the very initial phases of a protogalactic starburst might be clean, but it is not clear how long such a "window of observability" would last. It is also not obvious that star-forming dwarfs at low redshifts represent good analogs of the high redshift protogiants. Weedman 1991 estimated the

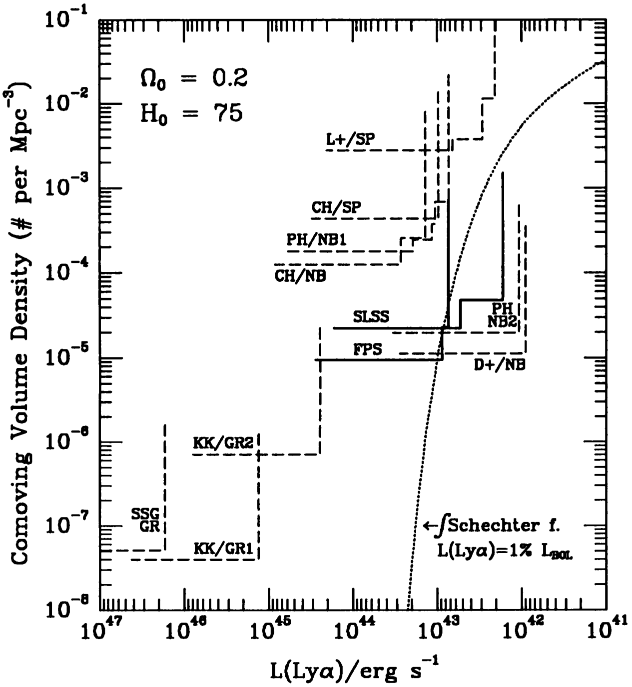


**Figure 2.** Limits from Figure 1, but with the observable coordinates translated into the comoving volume number density and restframe Ly$\alpha$ luminosity, using the same cosmology. The limits correspond to the central redshift in a given survey; accounting for the finite depth would tilt or curve the limit lines. The dotted line is an integral of the $z = 0$ Schechter luminosity function (i.e., no density evolution), assuming that there is no luminosity evolution and that 1% of the $z = 0$ bolometric luminosity is radiated in the Ly$\alpha$ line. This is probably a very pessimistic model, but even so, several surveys are already in conflict with its predictions.

fraction of escaping UV photons for a sample of Markarian starburst galaxies, and found that a large fraction of them must be relatively unobscured. There is some evidence that *disks* at $z \sim 2$ were at least moderately dusty, with the Ly$\alpha$ emission depressed (Pei et al. 1991; Elston et al. 1991; Charlot & Fall 1991). However, forming ellipticals and bulges could have been different, e.g., with the ISM fully reionized. Finally, we already know numerous Ly$\alpha$-luminous and star-forming galaxies at large redshifts, with no signs of extinction in their extended Ly$\alpha$ and UV nebulosities.

Perhaps the best argument against completely obscured star formation in PGs is the absence of a detectable sub-mm background in the COBE data (Mather et al. 1990). A crude, but robust argument is as follows: energy density today, deposited in a hypothetical sub-mm background (FIR in the restframe) by a population of dusty PGs is $u_{smb} = 7 \times 10^{-14}(\Omega_\star/0.02)(H_0/75)^2(1+z_{gf})^{-1}$ erg/cm$^3$, where $\Omega_\star$ is the fraction of the critical density in the stars in ellipticals and bulges (Djorgovski & Weir 1990). This should be compared with the present limits from COBE, $u_{smb} < 0.003\ u_{CMBR} = 1.3 \times 10^{-15}$ erg/cm$^3$. Even stronger limits could be obtained by fitting predicted sub-mm backgound spectra with the

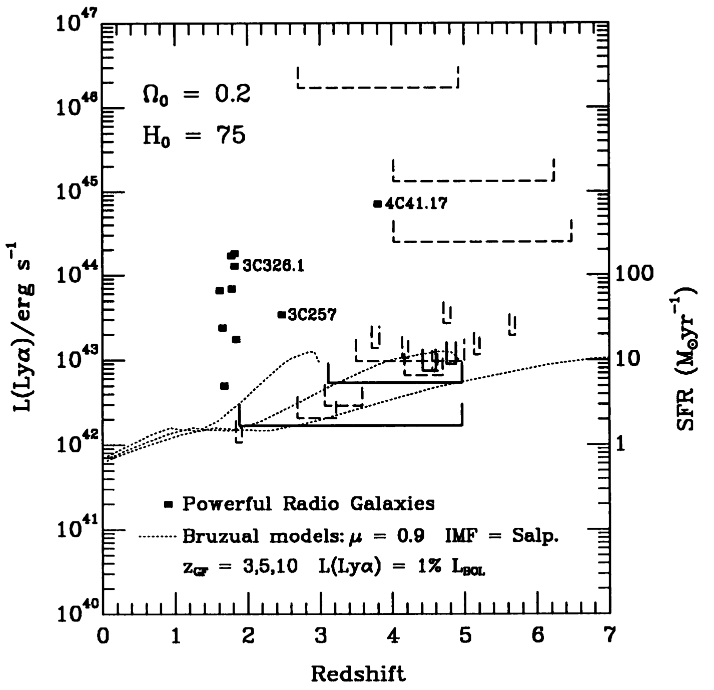


**Figure 3.** The sensitivity of PG surveys, expressed as the limiting Ly$\alpha$ line luminosity as a function of redshift, computed in the same way as in Figure 2. The solid lines are the limits from our long-slit (large $z$ coverage) and Fabry-Perot (two small $\Delta z$ windows), and the dashed lines are limits from other surveys. This figure contains no information on the area or volume coverage, and is complementary to Figure 2. Solid dots represent some of the powerful, Ly$\alpha$ luminous radio galaxies at high redshifts. Objects with line luminosities an order of magnitde or two lower could have been detected in the surveys to date. The dotted lines represent Bruzual $\mu = 0.9$ models for a galaxy with the initial $M_{gas} = 10^{11} M_\odot$ (roughly, a normal ellptical), assuming that only 1% of the total bolometric luminosity emerges in the Ly$\alpha$ line, and starting at $z_{gf}$ = 3, 5, or 10. The corresponding Ly$\alpha$ line luminosities powered by star formation of 100, 10, or 1 $M_\odot$/yr are indicated on the right.

COBE limits as a function of wavelength, e.g., by reversing the procedure described by Djorgovski & Weir 1990. We conclude that at most a few percent of the observed stars in $z \sim 0$ ellipticals and bulges could have been formed in dusty PG starbursts similar to those in IRAS galaxies today, or cooler. If at least some dark matter is baryonic, these limits would be stronger. However, the limits can be relaxed somewhat if the starbursts happened at $z < 3$, and the dust in them was considerably hotter than in their present-day counterparts. If there were dusty PGs at high redshifts, they may be detectable from the ground using sub-mm telescopes with the next-generation detectors and bolometer arrays.

We are driven to other possible explanations for the absence of Ly$\alpha$-luminous PGs in surveys to date. One possibility is that PGs were only slightly dusty – just enough to depress the Ly$\alpha$ below the present limits, but not enough to leave an imprint on the CMBR spectrum. Another possibility is that protoellipticals and protobulges are to be found at higher redshifts, $z_{gf} > 5$, which have been poorly explored so far. If either was the case, we may expect to see a new population of objects in deep near and mid-IR surveys, perhaps appearing at $K \sim 23^m$. This is just beyond the horizon (cf. Collins & Joseph 1988, or Cowie et al. 1990), and may be doable from the ground with the forthcoming 8 – 10 m telescopes, or with the HST/NIC. If $z_{gf} > 10$, deep surveys at 3 – 10$\mu$m with ISO and SIRTF may be able to detect them (cf. Franceschini et al. 1990).

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**Discussion:**

**R. Terlevich:** (1) Our work on nearby HII regions and HII galaxies indicate that the strongest signature in the UV spectrum of a young system is the stellar continuum and not the Ly$\alpha$ emission. Also, when performing magnitude-limited surveys, the first objects to be found are the brightest and *not* the $L_*$ ones. So, your detection limits are too pessimistic by perhaps 3 mag or more. (2) Your claim during your presentation that no quasar shows an absorption line type of spectrum to the blue of Ly $\alpha$ (when you presented the 28,000 sec spectrum), is in contradiction with observations of deep Ly$\alpha$ forest depression in quasars at $z \sim 4$, about 20% of them showing the Ly limit cut-off.

**Djorgovski:** On (1): I basically agree with you that the most likely explanation for the absence of numerous Ly$\alpha$ galaxies at $z \sim 2-5$ is dust extinction, although that is not the only possibility. On (2): You misunderstood me, what I said is the cutoff at $\lambda_{rest} = 912$Å, which is characteristic of stellar populations, but is not strongly present in quasars.

**Zinnecker:** Has the redshifted Ly$\alpha$ line been detected in IRAS 10214+4724? In view of the large amounts of dust implied by being an IRAS source, this would be very surprising.

**Lonsdale:** There is a spectrum of it with a weak Ly$\alpha$ – it is significantly fainter than C IV. The formal reliability of the optical identification is probably about 80% based on the magnitude of the galaxy and the size and distance of the error ellipse. There is a firm radio detection of the galaxy which raises the reliability of the identification with the IRAS source.

**Bershady:** Is there an overwhelming evidence against the possibility that ellipticals and bulges formed their first generation of stars in more diffuse systems? And if so, it would be important to express the Fabry-Perot limits in terms of surface brightness.

**Djorgovski:** Certainly, the formation of ellipticals probably did involve lots of merging. However, the metallicity gradients and the high central luminosity and phase space densities argue that a substantial fraction of the initial star formation occured within relatively compact regions. If one wishes to consider amorphous, well-resolved objects akin to 3C326.1, then our flux limits are less stringent by about a factor of 2 or 3.

**Spergel:** The high central densities in the core of ellipticals and in spiral bulges argue for a high redshift of galaxy formation: $z \sim 10 - 100$. In non-gaussian models such as the textures, galaxy formation begins at these high $z$'s. I would encourage observers to devise strategies for detecting galaxy formation at high $z$.

**Djorgovski:** Most searches to date were confined to the optical window (Ly$\alpha$ at $z \sim 2-6$) simply because of the technical limitations. I certainly agree that the next frontier is in the IR, corresponding to a high $z_{gf}$.

**Rocca-Volmerange:** Calculations of transfer through the Ly$\alpha$ emission line show that profiles could be very narrow at such distances, and so undetectable (Valls-Gabaud & Beujaffel 1991). What do you think about that?

**Djorgovski:** Ly$\alpha$ line widths are not very critical for most surveys; typical instrumental resolution is of the order of 1000 km/s. The most important selection effect is the line flux.

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