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The Search for Primeval Galaxies

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ABSTRACT. Isolated examples of young star-forming galaxies have been discovered, but the predicted widespread population of primeval galaxies (estimated to have surface densities in the range $10^{4\text{-}5}$ deg^{-2}) has so far escaped detection. The search for this extensive (and, so far, elusive) population concerns the formation of spheroidal systems (bulges and halos), since there is considerable evidence that disk formation was more quiescent. The review begins with a summary of the expected model independent properties of primeval galaxies. Particular attention is paid to the redshift of galaxy formation; empirical evidence is presented that supports galaxy formation at $z<5$; however, there exist persuasive arguments that at least *some* galaxy formation must have taken place at higher redshifts. A major part of this review concerns primeval-galaxy search strategies. Most (although not all) constraints on the properties of primeval galaxies come from searches for Lyman-alpha-emitting objects. Flux limits for these searches have now reached levels at which surveys should, according to simple models, have detected a total of 10^{1-3} objects, yet no really good candidates have been found. This discrepancy between models and observations can possibly be explained by a combination of (i) dust absorption, and (ii) finite angular extent, which degrades flux limits. Technological advances in submillimeter instrumentation should result in the detection of the far-IR flux of primeval galaxies in the next few years.

1. INTRODUCTION

The simplest definition of a primeval galaxy (PG) is "a galaxy viewed during its formation." The precise meaning of "formation" depends, however, on one's vantage point. Perhaps the most exact meaning of formation is "assembly of mass," as Peebles (1989) has emphasized; but mass assembly may be extraordinarily difficult to observe if the only release of energy during this phase is radiation of gravitational binding energy. A more pragmatic definition of formation epoch is that time at which a PG is at or near maximum luminosity. By the time this phase has been reached, a great deal of information about the earliest history of protogalaxies may have already been erased. But, at the present stage of our understanding of PGs, this may be the only period of PG evolution that we have a chance of observing.

Why search for primeval galaxies? There are many gaps in our understanding of galaxy formation (e.g., review by Silk and Wyse 1993); an empiricist's approach to improving our understanding of galaxy formation theory would be simply to search for PGs, and then compare the observed properties of these PGs with theoretical expectations. In other words, studying PGs can provide important constraints on galaxy formation theory. Furthermore, studying forming galaxies *in situ* provides information on the formation of stars under very different conditions than found locally, and hence may ultimately provide important insight into star formation theory. Finally, the search for PGs *may* eventually lead to the discovery of objects at $z>5$, and studying these objects should provide important insight into the physical processes that obtained at such redshifts.

As will be discussed in Sec. 2.6, there are many objects now known to possess properties that resemble the predicted characteristics of PGs. However, the problem is not one of locating such objects, which have been recognized in various surveys because of one or more extreme characteristics. Rather, the problem is to find the expected *widespread* population of galaxies undergoing their first starburst; these objects are expected to be numerous ($\sim 10^{4-5}$ deg^{-2}) and relatively bright (apparent magnitude $\approx +24$ in the *AB* system[1]), yet this pervasive population has so far eluded detection. *This* is the basic problem facing observers: where are these objects?

The first part of this review will concentrate on the predicted (and, to a surprising degree, model-independent) properties of PGs (Sec. 2), with special attention to the problem of the redshift of galaxy formation. This paper will then turn to known isolated PG candidates (Sec. 2.6) and PG models (Sec. 3). Finally, a discussion of PG searches (Sec. 4), complications (Sec. 5), and future search strategies (Sec. 6) will be presented.

Several excellent discussions on primeval galaxies and related topics have appeared over the past few years (Koo 1986; Djorgovski and Thompson 1993; Djorgovski 1992). The reader is also referred to excellent reviews of galaxy formation and related subjects by Cowie (1988), White (1989), Larson (1990, 1992), and Silk and Wyse (1993).

[1]The *AB* magnitude system (Oke 1974) is used throughout this paper. In this system, a flux of 3.63×10^{-20} erg cm^{-2} s^{-1} Hz^{-1} corresponds to $m_{AB}=0$, regardless of the wavelength of observation. Corrections to convert to the standard Johnson *UBVRI* system are -0.8 mag (*U*), $+0.2$ (*B*), 0.0 (*V*), -0.3 (*R*), and -0.5 (*I*).

2. PROPERTIES OF PRIMEVAL GALAXIES

To find a PG, one must have some idea of what one is searching for. Here we discuss a few of the (more or less) model-independent properties of PGs, and the relation of these properties to search strategies.

2.1 Surface Density

Suppose that PGs are found only at redshift $z_{\rm PG}$, and have a lifetime in a "recognizable PG phase" of $\Delta t_{\rm PG}$. Further suppose that the present-day descendants of PGs possess number density n_0 at the present epoch. The number of PGs visible in a solid angle $\Delta\omega$ can then (neglecting mergers) be written as

$$N = n_0(1+z_{\rm PG})^3 d_A^2 c\,\Delta t_{\rm PG}\Delta\omega, \tag{1}$$

where d_A is angular-diameter distance. Now, the luminosity density of the Universe (in B) is $\sim 2.4\times10^8\ h\ L_{B\odot}\ {\rm Mpc}^{-3}$ (Felten 1985), and the characteristic luminosity of galaxies is $L_B^* \simeq 1.6\times10^{10}\ h^{-2}\ L_{B\odot}$ (very similar to the luminosity of the Milky Way), where $h=H_0/100$ and H_0 is in km s^{-1} Mpc^{-1}. Hence a reasonable estimate for the local number density of L^* galaxies is $n_0 \simeq 0.015\ h^3\ {\rm Mpc}^{-3}$. The surface density of PGs can therefore be written as

$$\sigma \approx 10^5 \left(\frac{n_0}{0.015\ {\rm Mpc}^{-3}}\right)\left(\frac{\Delta t_{\rm PG}}{10^9\ {\rm yr}}\right) h_{50}\ {\rm deg}^{-2} \tag{2}$$

for $\Omega_0=1$ and a redshift of galaxy formation $z_{\rm PG}=5$. (Here h_{50} is the Hubble constant expressed in units of 50 km s^{-1} Mpc^{-1}. The choice of $z_{\rm PG}$ and $\Delta t_{\rm PG}$ in this formula will be justified below.) The numbers are even larger in an open Universe. Thus the progenitors of galaxies like the Milky Way should be very numerous, regardless of the exact choice of parameters in Eq. (2).

2.2 Spectrum

Meier (1976) first demonstrated that the flux F_ν of an object with a constant star-formation rate was roughly flat between the Lyman and Balmer breaks, with F_ν proportional to the star-formation rate in this spectral region. This result is usually expressed as (e.g., Meier 1976; Cowie 1988; White 1989)

$$F_\nu \simeq 2.6\times10^{27}\left(\frac{\rm SFR}{1\ M_\odot\ {\rm yr}^{-1}}\right) {\rm erg\ s^{-1}\ Hz^{-1}} \tag{3}$$

in the wavelength range 1000–3600 Å, for a Salpeter (1955) initial mass function (IMF).[2] There is some dependence of Eq. (3) on burst age and IMF, but in all cases the variation is less than a factor of 3 in F_ν (White 1989). We adopt Eq. (3) for the purposes of this paper, with the implicit understanding that this is probably a conservative estimate of F_ν.

Some spectral energy distributions (SEDs) of stellar populations with a constant star-formation rate of 1 $M_\odot$ yr^{-1} are

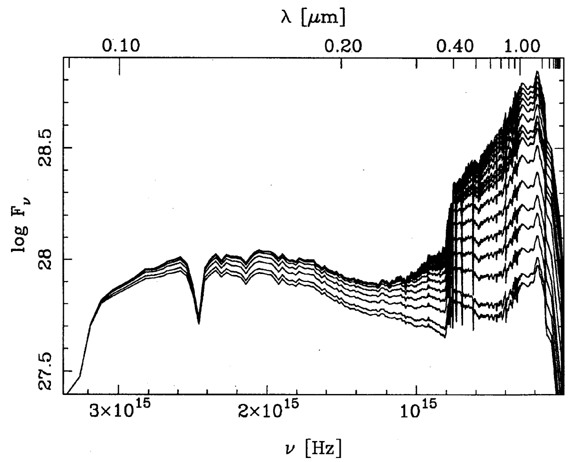

FIG. 1—Spectral energy distributions for stellar systems with a constant star-formation rate of 1 $M_\odot$ yr^{-1} (from the models of Bruzual and Charlot 1993). The ages of these systems range from 4×10^7 (bottom) to 10^{10} yr (top). The vertical axis is in units of erg s^{-1} Hz^{-1}. The prominent absorption feature near 1216 Å is Lyα. Note the relatively flat energy distribution from 1000 to 3600 Å; also note that the flux level over this wavelength range does not depend strongly on age. The total flux in the wavelength range 1000–3600 Å varies between 75% (4×10^7 yr) and 40% (10^{10} yr) of the total light beyond the Lyman discontinuity.

shown in Fig. 1 (from the models of Bruzual and Charlot 1993). The main contributors to the light at $\lambda<3600$ Å are upper-main-sequence stars; at longer wavelengths there is also a contribution from supergiants, asymptotic-giant branch, and finally giant stars as age progresses. However, the contribution of these populations never completely dominates the total energy output (at least for galaxy ages less than $\sim 10^{10}$ yr), provided that the star-formation rate remains roughly constant. Ignoring light below the Lyman discontinuity, the fraction of the total luminosity in the wavelength range 912–3600 Å varies from 75% at an age of 4×10^7 yr, to 60% at 10^9 yr, to 40% at 10^{10} yr. (This ignores dust—see below.)

A typical PG will contain many individual star-formation regions, and so the overall star-formation rate should be smoothly varying on time scales longer than the age of the most massive stars and shorter than the collapse time $t_{\rm coll}$ ($\sim 10^9$ yr). Thus it seems reasonable to characterize a PG by some mean star-formation rate, from which a rough estimate of $\langle F_\nu \rangle$ follows. In the Baron and White (1987, hereafter BW87) galaxy-formation scenario (see below), the star-formation rate is in fact predicted to be roughly constant over nearly one collapse time.

One effect that might cause a real PG to deviate from the idealization of Eq. (3) is dust absorption. One magnitude of absorption in the V band is roughly equivalent to 4.4 mag of absorption at 1000 Å (e.g., Seaton 1979). (This is illustrated in Fig. 2.) The absorbed UV radiation is reemitted thermally at wavelengths of order 100 μm, as in starburst galaxies. The relevance of this to PG searches will be discussed further in Sec. 6.

The flux predicted by Eq. (3) is from stellar photospheres alone. Real PG spectra will also show strong emission lines

[2]The models of Bruzual and Charlot (1993) give about 2–3 times more flux than predicted by Eq. (3), most likely because the upper-main-sequence models that they used included mild convective overshooting, which lengthens main-sequence lifetimes (Charlot, private communication).

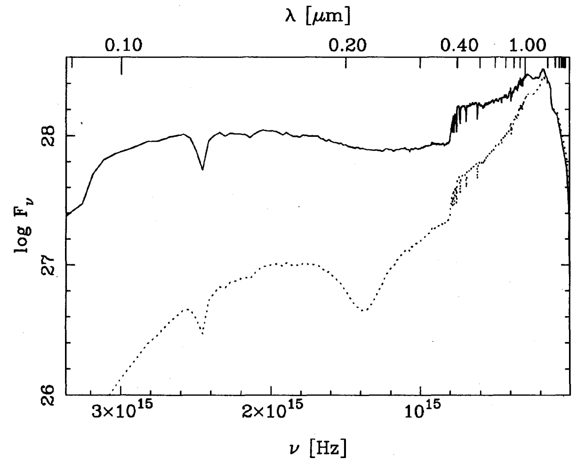

FIG. 2—The effect of 1 mag of V-band absorption on the spectral energy distribution of a 10^9-yr-old stellar population with constant star-formation rate. The *solid line* shows the SED with no absorption, whereas the *dotted line* includes absorption. The absorption law is the Galactic extinction model of Fitzpatrick (1986) for $\lambda<3600$ Å, with modifications to match the absorption measurements of Nandy et al. (1975) at longer wavelengths (see also Seaton 1979). The basic unabsorbed model is from Bruzual and Charlot (1993).

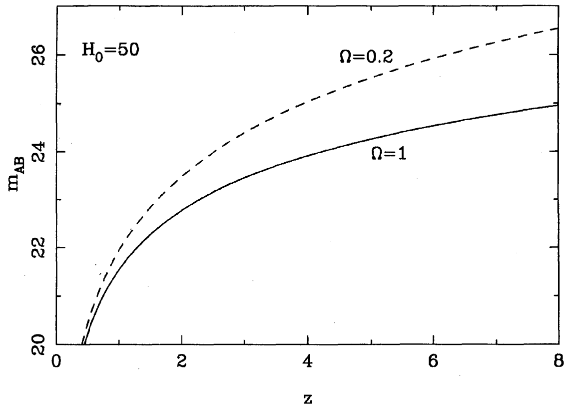

FIG. 3—The AB magnitude of objects with a constant star-formation rate of 100 $M_\odot$ yr^{-1}, as a function of redshift. [In this magnitude system $m_{AB}=0$ corresponds to $f_\nu=3.63\times10^{-20}$ erg cm^{-2} s^{-1} Hz^{-1}; see Oke (1974).] A Hubble constant of 50 km s^{-1} Mpc^{-1} is assumed for this diagram; the dashed line is for $\Omega_0=0.2$, whereas the solid line corresponds to $\Omega_0=1$. This diagram is based on Eq. (4), and hence assumes that the wavelength of observation corresponds to a rest-frame wavelength between the Lyman and Balmer discontinuities.

due to excitation of gas by UV photons from hot stars. A simple calculation based on Kennicutt's (1983) calibration of Hα strength versus star-formation rate, coupled with an Hα to Hβ intensity ratio from Case B recombination theory, and with F_ν from Eq. (3), yields a Lyα equivalent width of ~200 Å (e.g., Djorgovski 1992). This implies that roughly 3%–6% of the bolometric luminosity from a PG should be emitted in Lyα. More detailed calculations by Charlot and Fall (1993) yield rest-frame equivalent widths in the range 100–200 Å (depending on the power-law exponent of the initial mass function), for a constant star-formation rate; these results are in quite good agreement with the simple empirical argument above. The intensity of other lines, such as [O II] 3727 Å, Hβ 4861 Å, [O III] 5007 Å, and Hα 6563 Å, is discussed in Thompson, Djorgovski, and Beckwith (1994); these lines are generally weaker than Hα, which itself is about 8–11× weaker than Lyα (Ferland and Osterbrock 1985) in the absence of dust.

2.3 Luminosity

The principal source of energy from PGs is the release of nuclear binding energy from fusion reactions in stars. Energy release from AGNs *may* be comparable, but the connection of the AGN phenomenon with galaxy formation is unclear, and the lifetimes of individual AGN sources are uncertain. Other sources of energy (such as gravitational binding-energy release from galaxy formation or star formation, or energy release from supernovae) are smaller by 1–2 orders of magnitude (Djorgovski and Weir 1990; Djorgovski 1992).

A crude estimate of the luminosity of a PG can be obtained as follows. A PG will convert a fraction $Z\approx-\Delta X$ of its hydrogen into metals; based on the metallicities of old disk stars, $|\Delta X|\approx0.01$. Approximately 1% of this mass is converted into photons by release of binding energy in nuclear reactions. The net bolometric luminosity of such a source is then

$$L\simeq6\times10^{44}\left(\frac{|\Delta X|}{0.01}\right)\left(\frac{M_{\rm PG}}{10^{11}\,M_\odot}\right)\left(\frac{\Delta t_{\rm PG}}{10^9\ {\rm yr}}\right)^{-1}\ {\rm erg\ s^{-1}},\quad(4)$$

where $M_{\rm PG}$ is here the *baryonic* mass of the PG. The apparent brightness of such a source at $z=5$ ($h_{50}=1$, $\Omega_0=1$) is about 2.8×10^{-15} erg cm^{-2} s^{-1}, or, in the AB magnitude system, $m_{AB}\approx24.5$.

A somewhat more accurate approach to calculating the continuum brightness of PGs is simply to use the relation between star-formation rate and F_ν in Eq. (3). The result of such a calculation is shown in Fig. 3 for two cosmologies and a star-formation rate of 100 $M_\odot$ yr^{-1} [implicit in Eq. (4) above]. It can be seen that the results of this calculation are in reasonable agreement with the simple arguments above.

Thus it appears that PGs may be visible in continuum light in the optical-near-infrared bands, but of course only *provided* that the wavelength of observation lies redward of the Lyman discontinuity—i.e., $\lambda\gtrsim(1+z)$ 912 Å. For example, for observations in the I band, PGs may be visible provided that $z\lesssim8$ (although the limiting magnitude of typical I-band surveys probably precludes observation beyond $z\approx4$). The situation is similar for ground-based observations in the 1–2.4 μm window: the sky brightness in the K band limits observations to $K<23$ or $m_{AB}<25$ (e.g., Gardner, Cowie, and Wainscoat 1993), so some PGs may be present in K-band continuum surveys.

It is of interest to consider the total surface brightness of PGs on the sky. One could approximate this quantity by simply multiplying the characteristic surface density of PGs [Eq. (1)] by their brightness [from Eq. (4)]. A more exact, more elegant, and physically more revealing approach is to consider the production of metals (Lilly and Cowie 1987; Cowie

1988). The basic point of this approach is that energy production and metal production are closely linked processes. From arguments similar to those leading to Eq. (4), it is straightforward to show that a production rate of metals of 1 $M_\odot$ yr^{-1} leads to a flux $F_\nu = 2\times10^{29}$ erg s^{-1} Hz^{-1}, with very little dependence on the choice of initial mass function. [Assuming a mean metal yield ~1% then leads to Eq. (1), with, however, some IMF sensitivity.] From this can be derived a surface brightness due to metal formation of

$$S_\nu = 2.1\times10^{-25}\left(\frac{\rho Z}{10^{-34}\ \mathrm{g\ cm^{-3}}}\right)\mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}\ deg^{-2}}, \tag{5}$$

where ρZ is the present-day density of metals in the Universe. With the indicated choice of ρZ (corresponding roughly to 1/3 solar metallicity—e.g., Cowie 1988), this works out to a surface brightness $\mu_{AB}\approx 31$ mag arcsec^{-2}. Note that this is not in conflict with actual measurements of the background light; for example, Dube, Wickes, and Wilkinson (1979) derive an upper limit to the V-band background nearly 100× brighter. [Other upper limits to background fluxes can be found in Fig. 2 of Cowie (1988) and Fig. 3 of De Jager, Stecker, and Salamon (1994).]

The limit from Eq. (5) ($\mu_{AB}\approx 31$ mag arcsec^{-2}) can be compared with background levels from known sources. From the number counts of Lilly, Cowie, and Gardner (1991), it can be seen that the surface brightness in galaxies (for a 1 mag bin) is $\mu_{AB}\approx 30.9$ mag arcsec^{-2} (at $B_{AB}=25$) and 30.0 mag arcsec^{-2} (at $I_{AB}=24$). (These levels do not depend strongly on magnitude because the logarithmic slope of galaxy counts is fairly close to 0.4.) It is therefore possible (although not proven) that a small fraction (<10%) of galaxies in faint galaxy surveys could be PGs.

2.4 Size and Morphology

The visual appearance of a PG has been subject to a great deal of speculation. If the observable PG phase were the end product of the monolithic collapse of a massive cloud of gas (as proposed by, for example, Eggen, Lynden-Bell, and Sandage 1962; see also Larson 1974), then the bulk of its star formation might occur in a small region kiloparsecs in size (where 1 kpc$\simeq$0.″2–0.″4, depending on z and cosmology, although not with great sensitivity); such an object would be close to being unresolved with a ground-based telescope. An extreme example of such a model, in which most star formation occurs in a very small region, is model A of Lin and Murray (1992).

On the other hand, some models of galaxy formation (e.g., BW87) predict that PGs will be lumpy in structure and extended in size, primarily due to the fact that in these models galaxy formation is a hierarchical process. The BW87 models predict PGs that are ~5–10″ in size, with individual knots that may be bright enough to be visible. An extreme model would be the case in which there are a very large number of star formation sites spread throughout a large, more or less uncollapsed halo; the individual star-forming subunits would not be visible as discrete entities. Such an object would have very low surface brightness (~30 mag arcsec^{-2}), a size of perhaps 10–20″, and would be *extremely* difficult to detect using conventional techniques. (Nevertheless, it seems plausible that at least some of the gas in such an extended configuration would find its way into a nuclear starburst by dissipation.)

2.5 Redshift of Galaxy Formation

The redshift of galaxy formation z_{GF} is of great importance in deciding on a PG search strategy, since z_{GF} determines both how bright a PG will be, and in what wavelength range a search should optimally be conducted.

In this paper we will concentrate, as do many other authors (BW87; White 1989), on the formation of *spheroidal* systems. There is in fact very good evidence that the formation of disks is more quiescent than that of spheroids (e.g., Gunn 1982), and that disks were never much brighter than they are today.[3] For example, Larson (1992) summarizes evidence that the mean SFR in the disks of nearby spirals (including the Milky Way—e.g., discussion in Majewski 1993) was never much more than twice the present value. Recent estimates of the gas consumption time scales in disks yield mean values ~7 Gyr (cf. Kennicutt 1983; Sandage 1986; Donas et al. 1987; see also discussion in Larson 1992). This is not too different from the ages of disks, suggesting that, with a modest amount of infall, the mean SFR need not have been too different from the present value. This is all supported by the observations of Cowie, Songaila, and Hu (1993), who present direct evidence of the gradual growth of disks. From their observations it appears that disks may have grown by a factor of ~2–4× in mass since $z\simeq1$.

There is also some evidence that the bulk of disk formation followed well after spheroid formation for the Milky Way (e.g., review by Norris 1989). The most direct information on this point comes from the work of Winget et al. (1987) on the low-luminosity cutoff in the white-dwarf luminosity function. From this work it appears that the age of the disk is most likely $\simeq$10 Gyr, which is significantly younger than the 13–17 Gyr ages associated with (most) globular clusters (cf. Bergbusch and VandenBerg 1992; Lee, Demarque, and Zinn 1990).

If the age of the Universe $T_0>14$ Gyr and the age of the disk is $\simeq$10 Gyr, then this suggests that the bulk of disk formation began in earnest at $z\lesssim1$. Now, if most disk formation took place in a short burst of activity at $z\lesssim1$, then the objects involved should stand out in existing faint-object redshift surveys (e.g., Lilly 1993; Colless et al. 1990, 1993), since they would have $m_{AB}\lesssim 22$–23. The fact that they do not appear in these surveys strongly suggests that these disks formed in a quiescent fashion over a much longer interval of time.

Thus in what follows we will consider the epoch of galaxy formation to be the time at which the spheroid forms. In this picture the buildup of the disk might be thought of as a manifestation of galaxy evolution rather than galaxy formation.

[3]A clear counterexample, however, is the Large Margellanic Cloud.

2.5.1 Some Simple Model-Independent Arguments

There are several arguments for the redshift of galaxy formation that are more or less independent of an assumed model for galaxy formation (Peebles 1989; see also Peebles 1993, Sec. 25). Most provide upper limits to the redshift of galaxy formation.

(1) Ω *argument.* For a Universe with $\Omega_0<1$, growth of structure begins to freeze out at a redshift marking the transition between Einstein–de Sitter expansion and linear expansion–i.e., at

$$1+z_{\rm GF}\gtrsim \frac{1}{\Omega_0}-1 \tag{6}$$

(e.g., Peebles 1980, Sec. 11). Thus at least some galaxy formation must occur at quite large redshift in a low-Ω Universe, although infall continues right up to the present epoch in such a cosmological model.

(2) *Overlap argument.* Consider the precursors of galaxies as spheres. At what redshift were these spheres just touching? The separation of galaxies at this epoch was $\sim 2f_cR$, where R is the radius of the halo of the Milky Way ($\sim$100 kpc), and f_c is the amount by which the proto-halo collapsed before forming stars. (Dissipationless collapse provides a lower limit on f_c of 2.) The present-day separation of L^* galaxies is $\sim n_0^{-1/3}$, where n_0 is the present-day number density of L^* galaxies (e.g., Sec. 2.1). Then

$$1+z_{\rm GF}\lesssim \frac{n_0^{-1/3}}{2R}\simeq 11\left(\frac{n_0}{0.01\ {\rm Mpc}^{-3}}\right)^{-1/3}\left(\frac{f_cR}{200\ {\rm kpc}}\right)^{-1}. \tag{7}$$

Clearly this is a reasonable *upper* limit to the redshift of galaxy formation for L^* galaxies.

(3) *Density argument.* An interesting constraint on $z_{\rm GF}$ for L^* galaxies is obtained by finding the redshift at which the mean density of galaxies at the present epoch was just equal to the density of the Universe. This is an *upper* limit on $z_{\rm GF}$ for any reasonable model of galaxy formation. For a galaxy with total (i.e., dark plus baryonic) mass $10^{12}\ M_\odot$, with total radius 100 kpc, the mean density is $\sim 2\times 10^{26}$ g cm^{-3}, or a factor of f_c^3 smaller before any collapse took place. The matter density of the Universe is

$$\rho(z)=0.5\times 10^{-29}\ \Omega_0\, h_{50}^2(1+z)^3\ \ {\rm g\ cm}^{-3}, \tag{8}$$

from which we find

$$1+z_{\rm GF}\lesssim 8\,\Omega_0^{-1/3}\ h_{50}^{-2/3}\left(\frac{f_c}{2}\right)^{-1}. \tag{9}$$

One could repeat the above considering baryonic matter only ($M\approx 10^{11}\ M_\odot$ within $R\simeq 10$ kpc for the Milky Way). From nucleosynthesis constraints (Walker et al. 1991) $\Omega_b<0.1$, and $f_c\gtrsim 10$ by noting that the initial radius of the perturbation must have been $\gtrsim$100 kpc. The result is very similar: $z_{\rm GF}\lesssim 10$.

(4) *Collapse argument.* Perhaps the most physically insightful of arguments is derived from consideration of an expanding perturbation in the early Universe. It is straightforward to show that the collapse time (time for a perturbation to expand with the Hubble flow, turn around, and collapse completely) is just

$$t_{\rm coll}\simeq \pi\left(\frac{R_{\rm max}^3}{2GM}\right)^{1/2}\approx 2.8\left(\frac{R_{\rm max}}{10^2\ {\rm kpc}}\right)^{3/2}\left(\frac{M}{10^{12}\ M_\odot}\right)^{-1/2}\ {\rm Gyr}, \tag{10}$$

where $R_{\rm max}$ is the radius of the perturbation at turnaround ($R_{\rm max}=f_cR\gtrsim 200$ kpc for the Milky Way). To convert to a redshift requires a choice of cosmology that gives a reasonable T_0: for example, if $T_0=13$ Gyr, then $z_{\rm coll}$ lies between 1.8 ($h_{50}=1$, $\Omega_0=1$) and 3.5 ($h_{50}=1.5$, $\Omega_0=0$) for galaxies like the Milky Way.

2.5.2 The Empirical Evidence

There is a strong body of empirical evidence that can be marshalled to place constraints on $z_{\rm GF}$, and also on the nature of PGs.

(1) *Redshift surveys.* A number of redshift surveys at faint magnitudes have been conducted over the past few years (e.g., Broadhurst, Ellis, and Shanks 1988; Colless et al. 1990, 1993; Lilly 1993; Tresse et al. 1993). From these surveys, it is clear that widespread galaxy-formation activity is *not* occurring at $z\lesssim 1$; otherwise PGs, given their brightness at $z\approx 1$ (e.g., Fig. 3) and their surface density [Eq. (2)], would appear prominently in current redshift surveys. Put another way, the Universe at $z\approx 1$ is not too dissimilar to the Universe at the present epoch (Peebles 1989).

That is not to say that some galaxy-formation activity is not still underway at the present epoch.[4] Individual low-luminosity objects undergoing an intense burst of star formation are seen nearby (e.g., H II region galaxies—Terlevich 1988; blue compact dwarf galaxies—Thuan 1987). A debate continues as to whether these objects really are undergoing their first burst of star formation, or whether there is an underlying old population (Thuan 1987; Keel 1988; Meurer, Mackie, and Carignan 1994). Nevertheless, these objects comprise a tiny fraction of all nearby galaxies. It should also be noted that a significant fraction of the metals in present-day galaxies appears to be produced by the faint blue galaxy population at $z<1$ (Cowie et al. 1988), although if these galaxies are low mass then their metal-enriched gas may be expelled. But these objects are *not*, we believe, the long sought-after primeval galaxies; they represent, rather, relatively recent galaxy evolution, possibly driven by mergers, of a low-mass galaxy population (e.g., Cowie, Songaila, and Hu 1993).

(2) *Cluster ellipticals.* The small scatter in the colors of cluster ellipticals in the Virgo and Coma clusters provides an interesting constraint on the redshift of formation of ellipticals (Bower, Lucey, and Ellis 1992). If galaxy ages differ typically by an amount of order their collapse time (i.e., $\Delta T_{\rm GF}\approx T_{\rm GF}$, where $T_{\rm GF}$ corresponds to $z_{\rm GF}$), then $z_{\rm GF}\gtrsim 2$ for luminous ellipticals. This lower limit on $z_{\rm GF}$ could be larger if any of the scatter in colors originated in intermediate redshift starbursts.

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[4]Nevertheless, galaxy-formation activity at $z=0$ must be nearly finished, because most (>90%) of the baryonic material locally appears not to be in the form of gas.

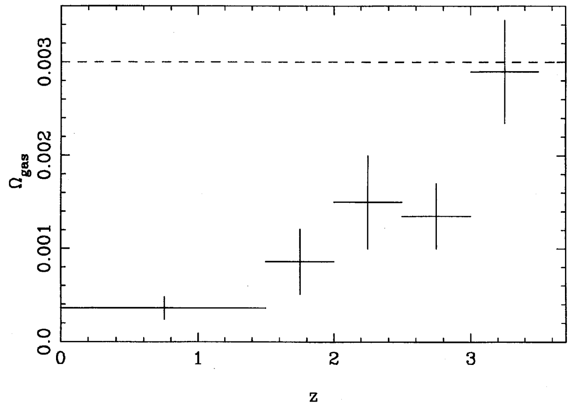

FIG. 4—The fraction of the critical density in damped Lyα absorbers, Ω_{gas}, as a function of redshift (from Lanzetta 1993; Lanzetta, Wolfe, and Turnshek 1994). The dashed line indicates the present-day density of luminous material (stars) in galaxies. It can be seen that most galaxy formation has taken place since z=3.5. This diagram is for H_0=100 km s^{-1} Mpc^{-1} and Ω_0=1; both the data points and dashed line scale as h^{-1}.

(3) *Milky Way globular clusters.* The ages of globular clusters in the Milky Way are now known to span a range of at least ~3 Gyr (cf. VandenBerg, Bolte, and Stetson 1990; Sarajedini and Demarque 1990). A reasonable assumption is that globular-cluster formation starts no earlier than the epoch of maximum expansion of a perturbation (t_{coll}/2). For a collapse time of $\gtrsim 10^9$ yr, the *midpoint* of the PG phase will then lie $\gtrsim$2 Gyr after the Big Bang, so that $z_{GF} \approx 2.5-4$ ($0.2 \le \Omega_0 \le 1$, $13 \le T_0 \le 15$ Gyr). In this picture the end of the formation phase would be 3.5 Gyr after the Big Bang, or at redshifts 1.5–2.2.

The above argument is probably one of the more powerful empirical arguments available on the epoch of galaxy formation, but it is not without problems. It is unclear whether the formation of globular clusters coincides with the formation of the halo/spheroid of the Milky Way, or, for that matter, whether there is a similar spread in ages found in field halo stars that would indicate a prolonged period of halo formation, independently of the globular clusters.

(4) *Damped Lyα absorbers.* Lanzetta and collaborators (Lanzetta 1993; Lanzetta, Wolfe, and Turnshek 1994) have studied the amount of gas in damped Lyα absorbers over a range of redshifts. Figure 4 plots their results for Ω_{gas}, the density in damped Lyα absorbers divided by the critical density, as a function of redshift; the present-day density of luminous material in galaxies and disks is shown for comparison. It can be seen that Ω_{gas} is very similar to the value of Ω computed for stars in galaxies at the present epoch. This result suggests that at least some damped Lyα systems originate in proto-spheroids; this is supported both by the short time scale of gas consumption in Fig. 4 ($\lesssim$1 Gyr), and also by the low mean metallicity of these clouds (see Lanzetta 1993 and Lanzetta, Wolfe, and Turnshek 1994 for further details).

If the damped Lyα absorbers really are the precursors of all modern-day galaxies,[5] as is suggested by Fig. 4, then it follows that *much of the stellar mass in galaxies formed between z=3.5 and 1.5*, and that perhaps half of these stars formed between z=2–3.

(5) *High redshift radio galaxies.* The SEDs of luminous, high redshift radio galaxies in principle offer an opportunity to determine their redshift of formation. There seem to be two distinct interpretations of the spectra of these radio galaxies (e.g., McCarthy 1993a); (i) they form at high redshift (z_{GF}>5), but are viewed at an epoch at which they are undergoing a small (in fractional mass) burst of star formation (Lilly 1988); or (ii) they are viewed shortly after their formation epoch (Chambers and Charlot 1990), a view that leads to estimates of z_{GF} more like 3–4. The remarkable tightness of the K-band Hubble diagram (Lilly 1989; McCarthy 1993a, Sec. 6.5) seems to argue for a relatively high $z_{GF} \gtrsim 5$; but this assumes no evolution in the masses of radio galaxies with redshift (see also discussion in Eales et al. 1993).

The most recent work on radio galaxies at high redshift indicates that the high z radio galaxies may well be a "mixed bag" in terms of origin. Very blue objects such as 0902+34 (Eisenhardt and Dickinson 1992) and the bluest objects in the survey of McCarthy (1993b) may have formation redshifts as small as 3–4 (see also Eales and Rawlings 1993). On the other hand, the reddest objects observed by McCarthy seem to require much larger formation redshifts. Nevertheless, these objects could have spurious colors due to nonstellar light or emission lines (Eales and Rawlings 1993). In addition, it appears that the colors of these objects are not, in any case, well matched by models (e.g., Fig. 2 of McCarthy 1993b). Given all of the above, plus the fact that radio galaxies are *not* typical of the general population of galaxies, we view constraints on galaxy-formation redshift from these objects with suspicion.

(6) *Cosmic microwave background radiation.* At a given epoch, small amplitude perturbations will take longer to grow into galaxies than large amplitude perturbations. Hence it follows that perturbations at $z \approx 1000$, and hence fluctuations in the cosmic microwave background (CMB), must be larger if z_{GF} is increased. In order not to violate the observed amplitude of CMB fluctuations, z_{GF}<3–4 for a CDM model (Kashlinsky 1993; Nusser and Silk 1993).

(7) *Quasars.* There are several ways of using quasars as indicators of the redshift of galaxy formation. For example, the peak in the space density of quasars lies around z=2–3 (e.g., Crampton, Cowley, and Hartwick 1987; Schmidt, Schneider, and Gunn 1991). If quasars are fueled by mergers (Carlberg 1990), and if mergers play an important role in galaxy formation (e.g., White and Frenk 1991), then it seems reasonable to suppose that the peak of the "galaxy-building" epoch lies at or around z=2. Note, however, that this argument associates no particular importance to quasars in rela-

[5]Songaila et al. (1994) have recently determined the deuterium to hydrogen ratio in a z=3.3 cloud towards a QSO. Their result implies a primordial $\Omega_b h^2$=0.005, where Ω_b is Ω in baryons; if this result is confirmed, then the damped Lyα absorbers must be the precursors of galaxies, because Ω_b (damped Lyα at z=3.5)$\approx\Omega_b$ (galaxies at z=0)$\approx\Omega_b$ (primordial).

tion to galaxy formation, other than as an indicator of the merger rate (but see Djorgovski 1994).

2.5.3 Redshift of Galaxy Formation—A Summary

As noted above, the two most interesting pieces of empirical evidence constraining the epoch of galaxy formation are (i) the age spread of Milky Way globular clusters, and (ii) a direct estimate of gas depletion (presumably due to star formation) from observations of damped Lyα absorbers towards QSOs. These two approaches yield characteristic epochs for the first burst of star formation for most galaxies around $z \approx 2-3$. Somewhat remarkably, this is in reasonable agreement with the predictions of the model-independent "collapse argument" above (for a collapse factor of 2), and with the existence of various "primeval galaxy candidates" discussed below. Furthermore, virtually all theories of galaxy formation in a CDM-dominated Universe predict galaxy formation at relatively low redshift (e.g., BW87; Carlberg 1988).

This moderately self-consistent picture is, however, disturbed by two recent papers by Turner (1991a,b), who convincingly demonstrates that the properties of quasars at high redshift *demand* at least some galaxy-formation activity at $z \gtrsim 5$. For example, the very existence of quasars at $z=5$ implies structure formation and collapse at much higher redshift. The fueling of QSOs at high redshift requires the existence of high overdensity perturbations in the accretion flow; otherwise the rate at which fuel can be supplied is too low. The high abundance of heavy elements in quasars at $z \gtrsim 4$ requires at least one generation of stars (and possibly two for nitrogen) to precede the quasar, and hence a redshift of galaxy formation certainly greater than 5 (see also Hamann and Ferland 1993).

A related argument is that the presence of heavy element absorption lines in the spectra of quasars implies that significant star formation and chemical enrichment has occurred along random lines of sight in the Universe *significantly earlier than* $z \simeq 4$. Finally, Hu and Ridgway (1994) have reported on the discovery of two extremely red $[(I-K)>6]$ galaxies. The simplest explanation of the SEDs of these objects is that they are ellipticals with an age $\gtrsim 3$ Gyr at a redshift $z \simeq 2.4$. This requires (conservatively) a formation redshift >6.

It seems most reasonable to conclude, then, that even if the bulk of galaxy-formation activity takes place at $z \lesssim 3.5$, there must still have been *some* galaxy-formation activity at higher redshifts. In fact, this is not at all unreasonable, since the spectrum of perturbations in the early Universe encompasses a wide range of amplitudes and mass scales.

2.6 Primeval Galaxy Candidates

As was discussed in Sec. 1, the principal focus of this review is on the detection of a widespread, high-surface-density population of PGs that should exist in all directions in the sky. Nevertheless, it is of interest to mention briefly some objects or classes of objects which have been proposed as candidate PGs.

We have already mentioned (Sec. 2.5) the possibility that QSOs or powerful radio galaxies might have been PGs at some stage of their evolution. There is also evidence that the somewhat weaker (~ 0.1 Jy) radio source 53W002 may be close to its initial star burst. This object was discovered in the Leiden–Berkeley Deep Survey, and was found to be a narrow-line galaxy with redshift $z=2.39$ (Windhorst et al. 1991). It appears to have started forming stars only ~ 0.5 Gyr earlier than its epoch of observation, placing the redshift of galaxy formation $z_{\rm GF} \simeq 2.7-4.2$, depending on cosmology (Windhorst, Mathis, and Keel 1992).

A class of superluminous, IR-bright galaxies has been identified that may be related to the PG phenomenon. The best-known member of this class is the $z=2.286$ IRAS galaxy F 10214+4724, which, with a bolometric luminosity of $>10^{14}\ L_\odot$, is one of the most powerful known sources in the Universe (Rowan-Robinson et al. 1991). Two other objects, though not as extreme, are now known to resemble F 10214+4724: P 09104+4109 at $z=0.44$ (Kleinmann and Keel 1987), and F 15307+3252 at $z=0.93$ (Cutri et al. 1994). The $z=3.8$ radio source 4C 41.17 (Chambers, Miley, and van Breugel 1990) is somewhat similar to the extent that it is extremely luminous ($L>10^{13}\ L_\odot$), appears to be undergoing an intense burst of star formation, and contains an enormous quantity of dust (Dunlop et al. 1994)—comparable to that observed in F 10214+4724. All of these sources can be interpreted as being powered either by starbursts (Brown and Vanden Bout 1991; Solomon, Downes, and Radford 1992; Rowan-Robinson et al. 1993), or by AGNs (Hines and Wills 1993; Elston et al. 1994). Regardless of the *dominant* source of luminosity, it seems plausible to suppose that these objects are massive elliptical galaxies in a very early stage of evolution (Kormendy and Saunders 1992); the observations of Elston et al. (1994) do not rule out substantial star formation, and are not in conflict with this interpretation. However, it is clear that not all PGs could be like these objects; otherwise a huge submillimeter background would result.

Damped Lyα absorbers may also be related to PGs, as discussed in the previous section. However, direct evidence of star formation in these objects is lacking, with the exception of ~ 3 absorbers that possess emission lines (Elston et al. 1991; Wolfe et al. 1992; Møller and Warren 1993). However, several Lyα sources have been discovered that are clustered around damped Lyα absorbers (e.g., Lowenthal et al. 1991; Macchetto et al. 1993; Møller and Warren 1993; see also Wolfe 1993). The Macchetto et al. object is a radio-quiet galaxy at $z=3.428$ with strong Lyα (rest-frame equivalent width $\gtrsim 160$ Å), and an inferred star-formation rate of 18 $M_\odot\ {\rm yr}^{-1}$. Both this object and the Lowenthal et al. object, which it resembles, are candidates for PGs.

3. MODELS OF PRIMEVAL GALAXIES

The empirically derived properties of PGs discussed in Sec. 2 can be compared with the predictions of several models. One of the first "modern" PG models was that of Meier (1976); this model was based on the hydrodynamic collapse computations of Larson (1974). Because of strong dissipation in these models, the prediction of Meier was that PGs were very compact, with a prominent core/halo structure.

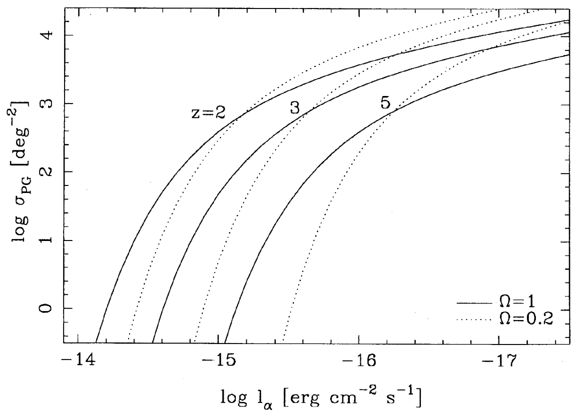

FIG. 5—The *integral* Lyα luminosity distribution; that is, the surface density of Lyα emitting objects *brighter than* a given Lyα flux. The models are computed for (top to bottom) $z=2$, 3, and 5. *Solid lines*: $\Omega_0=1$; *dotted lines*: $\Omega_0=0.2$. The model is described in Pritchet and Hartwick (1990), and assumes a collapse time $t_{\rm coll}=10^9$ yr, spheroid fraction $f_s=0.3$, $\phi^*=0.012$ h^{-2} Mpc^{-3}, and filter bandwidth $\Delta z=0.1$. The models are not sensitive to the value of H_0. Sensitivity of the models to other parameters is explored in Fig. 1 of PH90. (Note that the models in PH90 must be multiplied by a factor of 4π in surface density.)

Many details of the appearance of PGs were worked out for the first time in this paper.

More recently, BW87 have developed a model for the appearance of PGs in a Universe in which galaxies are dominated by dissipationless, pregalactic dark matter—e.g., CDM (see also Carlberg 1988). They ran an N-body simulation containing both gas and dark matter, assumed a completion of the collapse at around $z_{\rm coll}=2$ (or higher for a bias factor $b\simeq 1$), and further assumed a star-formation time scale $t_{\rm SFR}\approx t_{\rm coll}$, with star formation induced during cloud–cloud collisions. [If $t_{\rm coll}<t_{\rm SFR}$, a pure disk system results, whereas if $t_{\rm coll}>t_{\rm SFR}$ then a pure spheroid results. Hence this assumption is both reasonable and essential. It is interesting to note that the model of Lin and Murray (1992; see below) provides a simple self-regulating mechanism to enforce this near equality of collapse and star-formation time scales.]

The result of the BW87 computation was a flattened, lumpy protogalaxy, with ~60% of the stars formed in 80% of the collapse time. For a Schechter (1976) luminosity function for present epoch galaxies, the Lyα luminosity function is also a Schechter function, with characteristic luminosity $L^*_{{\rm Ly}\alpha}\approx 10^{43}$ erg s^{-1} for a rest-frame Lyα equivalent width of 100 Å and collapse time of 1 Gyr (BW87; Pritchet and Hartwick 1990). Figure 5 shows the expected *integral* Lyα luminosity function of PGs for different redshifts of collapse (for a filter bandwidth $\Delta z=0.1$).[6]

A somewhat similar model has been proposed by Lin and Murray (1992, hereafter LM92). This model is based on a more detailed treatment of star formation: star formation is *self-regulated* due to the fact that, for much of the PG phase, the cooling or star-formation time scale is less than the dynamical time scale. As a result, massive stars will form at a rate just sufficient to keep the ISM of the PG ionized (since ionization and heating of the ISM quenches star formation). The model neglects the gravitational effect of dark matter, and treats galaxy formation as being due to the collapse of a large monolithic perturbation (i.e., it neglects the substructure and mergers that are so important in the BW87 model).

The properties of the LM92 model depend dramatically on the initial configuration of the gas mass. However, a 10^{11} $M_\odot$ gas cloud that starts off as an isothermal sphere (an initial configuration that might be imposed, for example, by a dark matter halo) maintains a roughly constant luminosity in ionizing photons $\sim 10^{43.5}$ erg s^{-1} for roughly 1 Gyr. This corresponds to $\sim 10^{44.5}$ erg s^{-1} in bolometric luminosity (cf. Meier 1976). This is almost identical to the luminosity of a 10^{11} $M_\odot$ baryonic mass PG predicted by BW87. In addition, the lifetime of the PG phase (~1 Gyr) is very similar in the two models.

The principal difference between the BW87 and LM92 models appears to be in appearance: LM92 predicts a strongly centrally concentrated PG, with a smooth, diffuse envelope, whereas the BW87 model naturally predicts a lumpy, extended appearance due to the presence of inhomogeneities and mergers.

4. PRIMEVAL GALAXY SEARCH STRATEGIES

4.1 Some Broadband Searches

The first PG searches were motivated by the models of Partridge and Peebles (1967), which suggested that PGs would undergo their first burst of star formation near the maximum expansion phase of a perturbation ($z\gtrsim 10$). Thus PGs were predicted to be large (~10″), red objects. Such sources were searched for by Partridge (1974); his seven candidate PGs all appear to be normal galaxies at $z\lesssim 0.3$ (Koo 1986). Davis and Wilkinson (1974) developed an innovative large aperture (~1000 arcsec^2) photometer to search for *fluctuations* in the background that might have been due to a high surface density population of diffuse sources. No evidence was found for such a population, down to a flux level of 0.5% of the red ($\lambda\approx 7500$ Å) night sky brightness for a 100 arcsec^2 source. Comparable flux limits were achieved in a search for fluctuations in the infrared K band ($\lambda\approx 2.2$ μm) by Boughn, Saulson, and Uson (1986); this survey is noteworthy insofar as it extended the search for PGs to much higher redshifts (possibly $\gtrsim 10$).

Further constraints on PGs and high redshift galaxies using broadband surveys may be found in Koo (1986), Tyson (1988), and Guhathakurta, Tyson, and Majewski (1990); see also Smith, Thompson, and Djorgovski (1993).

4.2 Quasars and PG Searches

Models of galaxy formation that included dissipation (Larson 1974) completely changed the search strategy for PGs. PGs were now predicted to be quite compact, and the question naturally arose as to whether there were any PGs lurking in surveys of quasars (e.g., review by Koo 1986; Koo and Kron 1988). The answer appears to be no: for example, none of the ~250 QSO candidates in the CFHT survey

[6]The models in Fig. 1 of PH90 should be scaled up by a factor of 4π in surface density to correct a numerical error.

(Crampton, Cowley, and Hartwick 1990) have spectra which could be placed in the PG category (Hartwick, private communication).

The question nevertheless remains as to whether QSOs themselves could be PGs. This conjecture has a long history that has been reviewed by Koo (1986 and references therein; Djorgovski 1994). Recently Terlevich and collaborators have revived this idea (e.g., Terlevich and Boyle 1993); they propose that quasars could be the luminous, star-forming cores of very young elliptical galaxies undergoing their first burst of star formation (but see Heckman 1991; Filippenko 1992). Perhaps a more plausible scenario is one in which the formation of a luminous AGN (powered by conventional means—e.g., infall onto a massive collapsed object) is both associated with and contemporaneous with galaxy formation (Djorgovski 1994): in this case some (though not necessarily all) quasars may be the beacons that signal galaxy formation.

4.3 Redshift Surveys

Deep redshift surveys are generically related to broadband searches for PGs, because the objects for which redshifts are obtained are first identified in broadband images. A number of such redshift surveys have been completed (e.g., Broadhurst, Ellis, and Shanks 1988; Colless et al. 1990; Lilly, Cowie, and Gardner 1991; Colless et al. 1993; Lilly 1993; Tresse et al. 1993), and several others are nearing completion. The limiting magnitudes for these surveys are typically $B \simeq 22.5$ (Colless et al. 1990, 1993), or $I_{\rm lim} \simeq 22.5$ (Lilly 1993) or 22.1 (Tresse et al. 1993). Many thousands of objects now have redshifts, and few if any have characteristics that could ambiguously lead to classification as a PG.

4.4 Searches for Redshifted 21 cm Radiation from Neutral Hydrogen

Gunn and Peterson (1965) first noted that a diffuse neutral intergalactic medium would produce an absorption trough at wavelengths shorter than Lyα in the spectra of high redshift quasars. The fact that no such trough is seen (e.g., Steidel and Sargent 1987) provides an extraordinarily sensitive limit to the cosmological mass density in a diffuse neutral IGM, $\Omega_{HI}<10^{-5}$: either the IGM is ionized (e.g., Miralda-Escudé and Ostriker 1990), or it is strongly clumped.

In the latter case it is in principle possible to search for redshifted 21 cm radiation from the expected structures (Hogan and Rees 1979). This topic is nevertheless somewhat orthogonal to the rest of this review, for several reasons. First, a typical ($\sim$mJy) sensitivity limit in redshifted 21 cm corresponds to a neutral hydrogen mass $\sim 10^{14}\ M_\odot$ at $z \gtrsim 3$—i.e., a protocluster rather than a protogalaxy. Second, objects observed in redshifted 21 cm are likely to be in an evolutionary stage preceeding the epoch at which stars start to form (in contrast to the other search strategies that we discuss). Finally, and perhaps most important, these searches implicitly assume as their starting point that massive objects have collapsed at early epochs—i.e., that structure forms in a "top-down" hierarchy, as proposed by, for example, Sunyaev and Zel'dovich (1975). In contrast, we have for the most part assumed in this review a "bottom-up" hierarchy of structure formation—a view that is supported by many lines of reasoning (e.g., Ostriker 1993). Nevertheless, a discussion of such objects is clearly relevant to any discussion of galaxy formation.

Searches for redshifted 21 cm radiation from H I in protoclusters have been reported by a number of groups (Davies, Pedlar, and Mirabel 1978; Bebbington 1986; Hardy and Noreau 1987; Noreau and Hardy 1988), at redshifts ranging from 3.3 to 8.4. Perhaps the most sensitive survey at the low end of this redshift range is that of Uson, Bagri, and Cornwell (1991a), who reach a detection limit of around $10^{14}\ M_\odot$ in neutral hydrogen. The null results that these authors report are not surprising if structure forms in a bottom-up manner—i.e., as expected in Universes dominated by CDM (but see Uson, Bagri, and Cornwell 1991b).

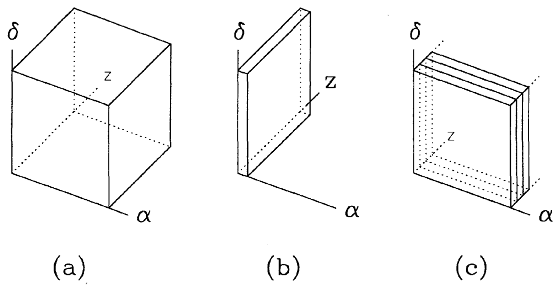

FIG. 6—Search strategies for emission line objects. (a) Slitless spectroscopy, (b) long-slit spectroscopy, (c) narrow-band imaging. Although the volume surveyed by slitless spectroscopy is largest of the three techniques, the limiting flux is brighter because each object is superimposed on a night sky background from all wavelengths passed by the optics.

4.5 Searches for UV-Optical Emission Lines

A PG can be thought of as a giant H II region that has been photoionized by massive stars from the first burst of star formation. Hence it is expected that PGs should possess a rich emission-line spectrum; even in the earliest (very low metallicity) phases of PG evolution one might expect strong Balmer and Lyman emission lines. One of the most intensively applied methods for detecting PGs is in fact searching for redshifted Lyα 1216 Å (Meier 1976; Hogan and Rees 1979), which we discuss extensively in this section of the paper. Other emission lines have been proposed for PG searches in the near-infrared (1–2.5 μm); these include [O II] 3727 Å (Thompson, Djorgovski, and Beckwith 1994), and Hα (Pritchet and Hartwick 1994), which is less affected by dust absorption than Lyα.

There are three principal search techniques for faint emission-line objects, illustrated in Fig. 6. The performance of these techniques is mainly distinguished by volume surveyed and by limiting brightness.

(1) Slitless spectroscopy [e.g., Fig. 6(a)] allows the sampling of a very large volume of space, but results in a relatively bright limiting threshold, because the sky brightness from *all* wavelengths passed by the bandpass of the system is superimposed on any spectral feature. This technique is com-

monly used in QSO grism/grens surveys (e.g., Crampton, Cowley, and Hartwick 1987, 1990), and two different PG searches using this technique have been reported by Koo and Kron (1980). These latter searches reach limiting fluxes $\sim 10^{-14}$–10^{-15} erg cm^{-2} s^{-1} and cover solid angles ~ 1 deg^2.

(2) Long-slit spectroscopy [Fig. 6(b)] generally results in the best limiting flux for detecting (unresolved) emission lines, because the spectral resolution, and hence sky background per resolution element, is lowest. However, the volume surveyed is usually much smaller than that achieved with other techniques. The principal long-slit surveys are those of Cowie and Hu (see Cowie 1988), Lowenthal et al. (1990), and Djorgovski and collaborators (Thompson, Djorgovski, and Trauger 1992; Djorgovski, Thompson, and Smith 1993). Typical limiting fluxes are 10^{-16}–10^{-17} erg cm^{-2} s^{-1}, and areas surveyed are $\lesssim 10^{-4}$ deg^2. Anecdotal evidence suggests that many other groups involved in faint-object spectroscopy have searched for serendipitous emission-line objects that happen to lie along their slits, without success. Pritchet and Hartwick (unpublished) have detected several such objects in long-slit spectroscopy with the CTIO 4-m telescope and RC spectrograph, but they are almost certainly low-luminosity [O II] 3727 Å emitters—i.e., "normal" intermediate redshift galaxies.

(3) Narrow-band imaging [Fig. 6(c)] imposes a restriction on Δz, the range of redshifts that is surveyed, and so results in a smaller surveyed volume. Most of this work consists of optical searches for Lyα at redshifts of order 2–6 using CCDs and narrow-band interference filters (e.g., Cowie 1988; Pritchet and Hartwick 1987, 1990; Rhee, Webb, and Katgert 1989; Smith et al. 1989; Wolfe et al. 1992; Djorgovski and Thompson 1992; Djorgovski, Thompson, and Smith 1993; De Propris et al. 1993; Møller and Warren 1993; Macchetto et al. 1993), or with a Fabry–Perot system (Djorgovski, Thompson, and Smith 1993; Thompson, Djorgovski, and Trauger 1992). The limiting flux for these surveys is much improved over slitless spectroscopy—typical flux limits are between 10^{-16} and 10^{-17} erg cm^{-2} s^{-1}, and typical CCD fields now approach 0.01–0.1 deg^2 (or larger for CCD mosaics) on 4-m class telescopes.

More recently narrow-band imaging surveys have been extended to the infrared. Pritchet and Hartwick (1994) have completed a CCD survey for redshifted Lyα at $z \approx 7$ ($\sim$9100 Å), and have achieved a remarkably faint limiting flux of $\sim 10^{-17}$ erg cm^{-2} s^{-1} by employing narrow-band filters designed to avoid the strongest OH emission lines (which are the dominant source of sky brightness in the region 7000 Å–2.3 μm). Using infrared arrays, Parkes, Collins, and Joseph (1994) have pushed the search for redshifted Lyα out to $z \approx 9$, using a similar "low OH" technique in the infrared J band; furthermore, Thompson, Djorgovski, and Beckwith (1994) have searched for redshifted [O II] 3727 Å emission from PGs associated with QSOs at $z > 4$. These latter two infrared array surveys reach limiting fluxes of order 10^{-15} erg cm^{-2} s^{-1}, over relatively small solid angles of 10^{-4}–10^{-3} deg^2 (the small sizes of the surveys being dictated by the small areas of infrared arrays, a limitation that is expected to improve in the future).

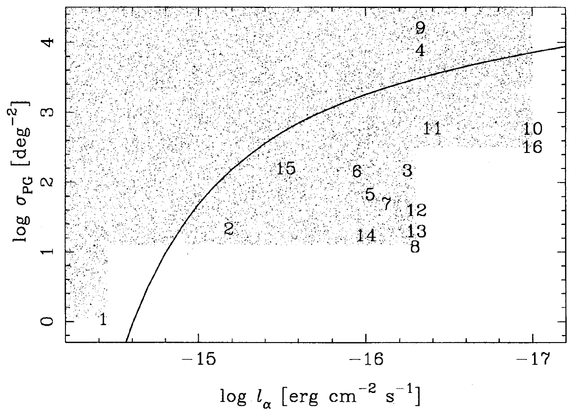

FIG. 7—Limits that have been placed on the surface density and apparent Lyα flux of PGs, from various searches for redshifted Lyα radiation. Each plotted number refers to a separate limit by a different group, and excludes the region to the upper left of the point (i.e., PGs can exist at fainter fluxes or lower surface densities). The shaded region combines the limits from different groups: The integral luminosity function of PGs should not pass through the shaded region. (In fact, the limits imposed by combining all of these surveys are even more stringent, because the surveys are independent.) The *solid line* is a model with $z=3$, $\Omega_0=1$, and other parameters taken from Fig. 5. This model should not be taken too seriously since the plotted limits refer to surveys at a range of redshifts (2–5). The meaning of the plotted numbers is as follows: 1, 2—Koo and Kron (1980) photographic and CCD; 3—Pritchet and Hartwick (1987); 4,5—Cowie (1988) long slit and narrow band; 6—Rhee, Webb, and Katgert (1989); 7—Smith et al. (1989); 8—Pritchet and Hartwick (1990); 9—Lowenthal et al. (1990); 10—Wolfe et al. (1992); 11,12,13—Djorgovski and collaborators (Djorgovski and Thompson 1992; Djorgovski, Thompson, and Smith 1993; Thompson et al. 1992, 1993) long slit, two Fabry–Perot surveys; 14—De Propris et al. (1993); 15—Macchetto et al. (1993); and 16—Møller and Warren (1993). See text for further details.

The result of all of these surveys is identical: *no emission-line PGs have been found.*

Figure 7 shows the constraints on surface density and limiting flux for observations of redshifted Lyα. (Similar diagrams have been presented by a number of authors—e.g., Koo 1986; Pritchet and Hartwick 1990; Djorgovski and Thompson 1992.) We have assumed that the upper limit on surface density is one object per sampled solid angle. The plotted points should be interpreted as excluding the region to the upper left of each point (higher fluxes *and* higher surface densities). The stippled area roughly combines the limits from different groups; PGs should possess lower fluxes and/or surface densities than the shaded area, and the integral PG luminosity function should not pass through this shaded region. (However, it should be noted that the survey limits plotted in Fig. 7 are independent, and hence the combined limit of all the surveys should be even stronger than the shaded area.)

The limits plotted in Fig. 7 are illustrative only. Different groups use different criteria for defining their limiting fluxes (in terms of both the number of noise σ for a real detection, and also the size of the image), and it is difficult to correct the published information to a uniform system.

The solid line in Fig. 7 represents a rough model computed as in Fig. 5. Insofar as the model cuts through the region excluded by the limits, this model appears to be in

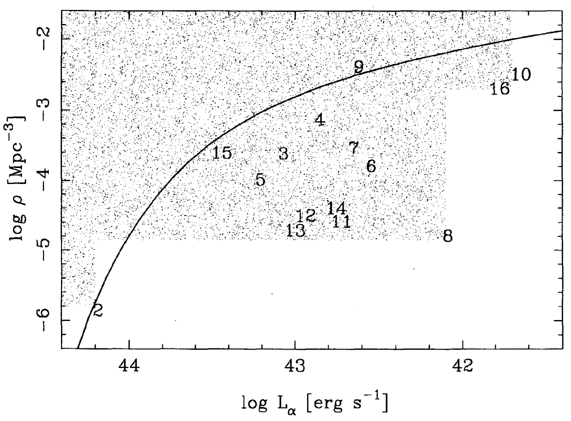

FIG. 8—Limits on PG comoving densities and absolute Lyα luminosities. These limits were computed assuming $h_{50}=1$ and $\Omega_0=1$. The model is as described in Sec. 3. The reference numbers for the limits, and the meaning of these limits and the shaded area, can be found in the caption to Fig. 7. See text for further details.

disagreement with the observations. However, this model has been computed for $z=3$, $\Delta z=0.1$, whereas the observations cover a range of redshifts ($z\approx 2-5$) and redshift intervals. To rectify this problem, we convert the observed surface density and flux limits into corresponding volume density and absolute luminosity limits (Fig. 8). In this diagram the limits can be compared with one model independently of $z_{\rm GF}$; the model in this figure is that described in Sec. 3 and used (in observational form) in Fig. 5. The meaning of the reference numbers is the same as in Fig. 7.

Again it can be seen that primeval galaxies as predicted by our simple dust-free model should have been easily detected if they were unresolved. The discrepancy between model and observations exceeds a factor of 100× in surface density, or 10× in luminosity, if galaxies formed in the redshift interval 2–5. The limits at higher redshift are not as strong at the present time.

5. COMPLICATIONS

5.1 Dust

Is strong Lyα emission really expected from a PG? A PG can be thought of as a giant H II region. A typical Lyα photon in an ionization-bounded H II region is resonantly scattered $\sim 10^6-10^7$ times before it leaks out (Osterbrock 1962). It follows that even a tiny admixture of dust in an H II region will erase nearly all Lyα emission, because the total path traveled by Lyα photons is $\sqrt{N}\approx 10^3\times$ longer than the "straight-through" radius of the H II region.

This expectation appeared to be borne out by early ultraviolet observations of starburst galaxies with *IUE*. Starburst or H II region galaxies might have been expected to be prodigious emitters of Lyα; yet the first observations of these objects (Meier and Terlevich 1981; Hartmann, Huchra, and Geller 1984; Deharveng, Joubert, and Kunth 1986; Hartmann et al. 1988) showed that their Lyα emission was weak, absent, or sometimes even in absorption. Thus they appeared to be excellent candidates for the type of excess absorption that might be associated with resonant scattering. The implication for PG searches was clear: Searches for Lyα emission from PGs were doomed to failure.

Nevertheless, it now appears that this simple picture of quenched Lyα emission from starburst galaxies and PGs may be oversimplified, for several reasons. Neufeld (1991) has argued that scattering in a multiphase medium results in a much larger equivalent width of Lyα than would result from resonant scattering in a homogeneous medium—possibly even exceeding the strength of Lyα that would be expected without resonant scattering.

The empirical evidence also no longer supports resonant scattering. An analysis of a larger sample of *IUE* observations of low redshift star-forming galaxies (including recent observations by Terlevich et al. 1993) suggests that the observed line strength ratio Lyα/Hβ is consistent with that expected from normal recombination theory and reddening laws (Calzetti and Kinney 1992; Valls-Gabaud 1993), but much larger than would be the case were resonant scattering of importance. There are also several classes of astronomical objects (other than QSOs) at large redshift known to have observable Lyα. Some (although not all) radio galaxies are known to possess strong Lyα emission, as do several companions to QSOs (Djorgovski et al. 1985, 1987; Steidel, Sargent, and Dickinson 1991; Hu et al. 1991). (In the latter case it is unclear whether the observed Lyα is excited internally or by the QSO itself.) One or two damped Lyα absorbers have now been detected in Lyα, as have some companions to damped Lyα absorbers.

Furthermore, van den Bergh (1990) has inspected CCD images (Pierce 1988) of 105 galaxies in the Ursa Major and Virgo clusters, and has noted that galaxies with metallicities [Fe/H]<-1 exhibit essentially *no* dust absorption. Thus a phase will always exist early in the history of a PG during which time it will be dust-free. For a constant star-formation rate (e.g., BW87), and for a final PG gas metallicity $Z\approx 1/3Z_\odot$ (as suggested by the maximum metallicity of the halo and the minimum metallicity of the disk), it follows that as much as $\sim$30% of the lifetime of the PG phase may be spent in a relatively dust-free state (see also De Propris et al. 1993). This suggests an empirical correction to the predicted numbers of observable Lyα emitting PGs that we conservatively estimate to be of order a factor 10 in surface density.

Finally, it is of interest to compare the predicted far-IR flux from dust-quenched PGs with observations (see also Djorgovski and Weir 1990; Bond, Carr, and Hogan 1991; Bond and Myers 1994; Blain and Longair 1993a,b; Wright et al. 1993). The *COBE* experiment has set an upper limit of $\sim 0.03\ \mu{\rm erg\ cm^{-2}\ s^{-1}\ sr^{-1}\ cm}$ on spectral distortions in the CMB blackbody spectrum over the wave-number range 2–20 cm^{-1} (wavelengths 0.5–5 mm). Now, the total background flux from PGs is expected to be $S\approx 2/(1+z)$ $\mu{\rm erg\ cm^{-2}\ s^{-1}\ sr^{-1}}$ [from Eq. (5), assuming a flat spectrum for rest $\lambda>912$ Å, and $\rho Z\simeq 10^{-34}$ g cm^{-3}]. The reemitted spectra of starburst galaxies (e.g., Arp 220, M82, F 10214 +4724) all appear to peak in I_ν near 100 μm. Hence a reasonable estimate for the peak submillimeter flux density from PGs is $I_k\approx S/k\approx 0.02\ \mu{\rm erg\ cm^{-2}\ s^{-1}\ sr^{-1}\ cm}$, *if* these PGs are *completely* shrouded in dust. (A more detailed calculation, taking into account the energy distribution of starburst galaxies, gives I_k a factor 2 smaller.) This can be compared with the upper limit on spectral distortions in the CMB blackbody of <0.03 in the same units (Mather et al. 1993). In other words, a substantial fraction of galaxy-formation activity could be hidden by dust, without violating *COBE* constraints on spectral distortions in the CMB blackbody fit.[7]

The overall conclusion of this section is that some fraction of PGs $\gtrsim 10\%$ should be visible in Lyα. Although dust shrouding in the late stages of PGs appears very probable, it does not significantly affect the current observational constraints.

5.2 Angular Extent

The limits quoted for emission-line sources in Sec. 4 were for point sources. Since virtually all observations referred to were acquired under sky-noise (or detector-noise) limited conditions, it follows that the limiting flux for PGs will vary roughly as $1/\sqrt{\Delta\omega} \propto 1/\Delta\theta$, where $\Delta\theta$ is a measure of the characteristic angular diameter of a PG. The characteristic size expected for PGs is quite uncertain (cf. Sec. 2.4); we will assume a maximum angular diameter of 5″, corresponding to about 30–40 kpc for $z=2$–5 ($h_{50}=1$, $\Omega_0=1$), and also corresponding roughly to the characteristic size of the $z=1.8$ radio source 3C 326.1 (McCarthy et al. 1987). This is roughly 5× larger than typical seeing disks at ground-based observatories, resulting in a shift of the data points to the left in Figs. 7 and 8 (i.e., towards brighter limiting fluxes).

Whether this angular extent is reasonable for a PG is unclear. For example, dissipation could result in a large concentration of gas towards the center of a proto-elliptical, something that agrees with the high luminosity and phase-space densities of ellipticals at the present epoch (Carlberg 1986), as well as the strong nuclear concentration of starbursts in nearby galaxies (Kormendy and Sanders 1992). The question of the angular size of PGs will only be resolved when a substantial population of these objects has been discovered.

5.3 Other Complications

Biasing (Kaiser 1986) could lead to a strong clustering of galaxy-formation sites, and hence a relatively small volume filling factor for PGs. Such an effect is in fact seen in dissipative n-body simulations (e.g., Evrard, Summers, and Davis 1994). It was this complication that De Propris et al. (1993) sought to avoid by searching for PGs near known structures at intermediate redshift (e.g., QSOs); however, the null results of some of the other work cited above could be caused by a random placement of fields. Clearly this should be considered when designing future PG search strategies (see discussion in Sec. 6.1).

[7] A somewhat different conclusion was reached by Djorgovski (1992). However, if his parameters are changed to match our calculation (efficiency of energy production from nuclear reactions $\epsilon=0.01$, $\Delta X=0.01$, $\Omega_*=0.001$ from the initial starbursts), the agreement with our conclusion is reasonable.

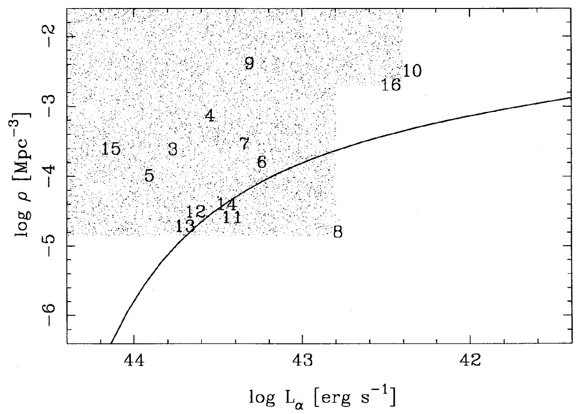

FIG. 9—As in Fig. 8, except that the effects of dust have been allowed for by reducing the predicted density of the model by 10×, and the effects of a 5″ object size have been taken into account by increasing the observed flux limits by 5×. See Sec. 5.3 for further details.

Another possibility that must be seriously considered is that we have completely miscalculated the expected optical appearance of PGs. For example, suppose that most proto-bulges and proto-ellipticals go through a luminous AGN phase immediately after commencing star formation (Djorgovski 1994). In this case PGs have already been found, and conventional PG searches are doomed! Or, suppose that the IMF of the initial burst of star formation were radically different from the Salpeter (1955) IMF. This could result in very different properties of PGs (e.g., no emission lines in the case of an upper mass cutoff, or an extremely brief luminous PG phase for an IMF biased towards massive stars).

5.4 Revised Comparison of Observational Limits with Models

Figure 9 shows a revised comparison of the observational limits on Lyα emission from PGs with models. This figure differs from Fig. 8 in that we have increased the individual flux upper limits by 0.7 in log L_α to allow for resolved structure (Sec. 5.3), and have moved the predicted model surface densities down by a factor of 10× in surface density to simulate the effect of dust absorption during 90% of the lifetime of a PG (Sec. 5.2).

The corrections that were adopted above for angular size and dust are quite uncertain, and are probably at or near the extremes of what would be considered reasonable. Nevertheless, the result is clear: With the above corrections *there no longer appears to be a significant discrepancy between model predictions and observations.* There remain other effects discussed above (clustering of PGs, confusion of AGNs and PGs) that are not taken into account in Fig. 9. In other words, the fact that we have not found a pervasive population of emission line PGs to date is probably not surprising.

6. THE FUTURE

6.1 UV/Optical/IR Surveys

Empirical evidence on the existence of high-redshift Lyα-emitting objects, and also on the incidence of dust absorption in low-metallicity galaxies, suggests that PGs may be visible in Lyα for some significant fraction ($\gtrsim$10%) of their lifetime. This conclusion, coupled with the observation that resonant scattering does not quench the Lyα emission of active star-forming galaxies beyond what is expected from a normal reddening law, seems to favor a continued effort to detect Lyα emission from PGs.

At present, emission-line surveys are just barely reaching the flux limits and volumes needed to detect $\sim 10^0$ objects. Currently the best prospects for searching for a widespread population of PGs appear to be in expanding the volume surveyed, either using mosaics of CCDs to increase solid angle coverage, or acquiring data for additional slices in redshift space. [An innovative and promising technique for expanding redshift coverage is the Fabry–Perot technique of Djorgovski and collaborators; this provides a narrow-band (hence very faint flux limit) tunable system.]

It appears unlikely that the flux limits can be pushed much fainter that the current limits of $\gtrsim 10^{-17}$ erg cm^{-2} s^{-1} in the optical ($\lambda < 7000$ Å). The one exception appears to be searches for unresolved objects, for which *HST* (or ground-based adaptive optics) observations may improve flux limits by factors up to $\sim 10\times$. At first sight it might appear that improved resolution would be of limited interest in searching for PGs, since this resolution (approaching $0\overset{''}{.}1$) would detect structures smaller than 1 kpc. However, at this level of resolution, and with the concomitant improvement in limiting magnitude for unresolved sources, it may be possible to detect the individual star-forming regions that comprise an otherwise large, low surface-brightness PG.

This raises the issue of detecting fuzzy, low surface-brightness PGs. In Sec. 5.2 we considered the detection of such objects as depending on Poisson statistics—i.e., $S/N \propto \Delta\omega^{-1/2}$. In fact, fuzzy objects are considerably more difficult to detect than this, because of flat fielding errors, reflections of bright stars by correcting optics, and perhaps even high latitude "cirrus" (Sandage 1976; Guhathakurta and Tyson 1989). Extracting limits on large faint PGs requires exquisite care, both at the telescope (improved flat fielding techniques, carefully choosing fields to avoid reflections and cirrus problems), and also during data reduction (e.g., using many shifted exposures to separate true objects on the sky from observational artefacts). Considerable work remains to be done in this area.

Most of the surveys for which limits appear in Figs. 7–9 have emphasized achieving a faint flux limit at the expense of volume coverage. It is therefore germane to consider a somewhat orthogonal approach to detecting emission-line PGs: searching for intrinsically luminous (but rare) sources in a very large solid angle survey. Such a survey is now underway using the UBC 2.4-m liquid mirror telescope, which will search over $\sim$20 deg^2 for emission-line PGs at $z=4.8$ in three 160 Å bands down to a limiting Lyα surface brightness of order 3×10^{-16} erg cm^{-2} s^{-1} arcsec^{-2} (Hickson 1994). Referring to Figs. 7–9, it can be seen that this large solid angle survey, which will probe a comoving volume $\sim 5\times 10^7$ Mpc^3, will provide extremely interesting constraints on the properties of PGs—constraints that are quite complementary to previous surveys.

Nath and Eichler (1993) have also proposed searching for redshifted blends of highly ionized [Fe VII]–[Fe XII] lines in the far UV (rest wavelengths $\lambda\lambda$160–200 Å); these lines are expected from hot diffuse (metal-enriched) gas heated to the virial temperature ($\sim 10^6$ K) of a PG by supernovae. The principal problem here appears to be dust absorption, which will affect these lines even more dramatically than Lyα: i.e., if the null results of Lyα surveys are due to "normal" dust absorption rather than resonant scattering (as argued above), then the probability of detecting these far-UV lines appears to be much lower than for Lyα (especially since they are metal lines, and the existence of metals implies the existence of dust).

An interesting continuum technique which deserves further study is the search for the Lyman discontinuity in faint galaxy populations (e.g., Koo and Kron 1980). This technique has already been used to advantage by Steidel and Hamilton (1993; see also Giavalisco, Steidel, and Szalay 1994) to identify candidate high-redshift galaxies clustered around a damped Lyα absorber; and Guhathakurta, Tyson, and Majewski (1990) use U-band photometry to rule out the existence of a large population of objects at $z>3$ with large Lyman continuum breaks. A new survey to detect objects with large Lyman discontinuities has been commenced by De Robertis and McCall (1994).

In addition to pushing the search for Lyα radiation out to ever increasing redshifts (Parkes, Collins, and Joseph 1994; Pahre and Djorgovski 1994), IR observations are of importance for detecting redshifted optical lines such as [O II] 3727 Å, [O III] 5007 Å, and Hα 6563 Å (Thompson, Djorgovski, and Beckwith 1994), all of which are less affected by dust than Lyα. Searches for PGs in the near infrared are fraught with difficulty, both because of the small physical size of IR detectors, and especially because of the poor flux limits imposed by the strong OH sky background. However, recent experiments in selecting narrow spectral regions with low OH emission are extremely encouraging. For example, the Pritchet and Hartwick (1994) survey at 9100 Å has reached a limiting threshold of $\sim 10^{-17}$ erg cm^{-2} s^{-1} for stellar objects, and recent observations by these two authors in a nearly OH-free window near 1.6 μm look very promising. A similar technique has been used in the infrared J band by Parkes, Collins, and Joseph (1994). Clearly a great deal of work remains to be done in this area, both by selecting additional low OH windows, and by observing with the next generation of large-format IR arrays to improve volume coverage.

Finally, it is relevant to consider the choice of fields in PG surveys (see also Sec. 5.3). Most groups have chosen random fields for PG searches, arguing that a widespread population of PGs should exist everywhere, and hence any field should be as good as any other. An interesting alternate approach is provided, however, by the work of Rhee, Webb, and Katgert (1989), De Propris et al. (1993), and Thompson, Djorgovski, and Beckwith (1994; see also Djorgovski, Thompson, and Smith 1993). In these studies, fields are chosen near objects known to exist at high redshift (e.g., QSOs); the redshift of the emission-line survey is then tuned to match the redshift of the QSO. The argument is that this is a volume of the

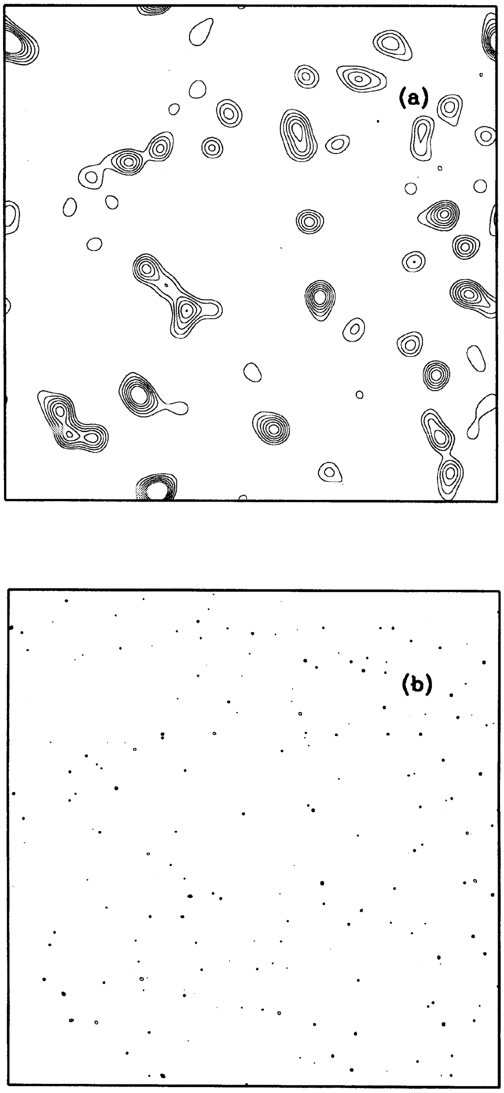

FIG. 10—A simulation of the appearance of the sky at a wavelength of 850 μm, from Bond and Myers (1994). Each simulation is 4 arc min on a side, with contours separated by 200 μJy. (a) Beam size 12″, lowest contour 1 mJy. The appearance of this figure corresponds roughly to the anticipated performance of the SCUBA receiver on the James Clerk Maxwell Telescope. (b) Beam size 1″, lowest contour 200 μJy. This corresponds to the expected performance of the Owens Valley Radio Observatory millimeter array.

Universe in which it is known *a priori* that structure has collapsed, and so the probability of encountering other collapsed structures is enhanced. This argument is essentially statistical biasing (Kaiser 1986), and finds empirical support both in the observation by Wolfe (1993) that Lyα emitting objects are clustered around damped Lyα absorbers with a probability far in excess of random, and, as noted above, in the fact that numerical simulations suggests that the volume filling factor of galaxy formation is $\lesssim 1\%$ (Evrard, Summers, and Davis 1994). Surveys near high-redshift QSOs may prove to be a useful method of detecting both primeval galaxies *and* protoclusters.

6.2 Millimeter and Submillimeter Surveys

Some of the most exciting opportunities for the future detection of the general population of PGs exist in the submillimeter and millimeter spectral regions. As discussed extensively above, it is possible and even likely that a significant fraction of the UV-optical emission from PGs is absorbed by dust and reradiated at longer wavelengths. The emission from these galaxies could even be totally obscured without violating CMB distortion constraints (e.g., Sec. 5.1). The presence of dusty galaxies at high redshifts is now well established (e.g., Sec. 2.6), and Dunlop et al. (1994) have detected an enormous dust mass in the $z=3.8$ radio galaxy 4C41.17, using the James Clerk Maxwell Telescope (JCMT) at a wavelength of 800 μm. The presence of a strong IR background (10–100 μm) consistent with obscured PGs has been inferred from an ingenious γ-ray experiment by De Jager, Stecker, and Salamon (1994).

With the new SCUBA array at JCMT (available late 1994), it should prove possible to detect sources as faint as 470 μJy per beam (1σ detection, 1-hr exposure, 800 μm). Since the flux from a $z=5$ PG of baryonic mass $10^{11}\ M_\odot$ is ~1.6 mJy (e.g., Sec. 2.3), it follows that the detection of such a source (which is ~10× fainter than 4C 41.17) should be straightforward. From the surface density estimates in Sec. 2.1, there should be ~5 such sources per $2'\times2'$ SCUBA field. Detailed simulations of the appearance of the sky in the submillimeter are shown in Fig. 10 for two instrumental configurations (Bond and Myers 1994). Such observations offer perhaps the best hope for detecting a widespread population of PGs in the near future.

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