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LYMAN-ALPHA EMISSION FROM GALAXIES

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ABSTRACT

We use new models of stellar population synthesis to compute the Lyα emission from galaxies with different star formation histories and initial mass functions. The models include all phases of stellar evolution and recent advances in the theories of stellar interiors and atmospheres. We find that dust-free galaxies would have Lyα equivalent widths of 50–200 Å, i.e., significantly higher than previous estimates, except from a few times 10^7 to 10^9 yr after a burst of star formation. We also consider several other factors that can affect the observed Lyα emission: the contributions by supernova remnants and active galactic nuclei, the orientation of a galaxy, and absorption by dust. We then use this framework to interpret the observations of and searches for Lyα emission from nearby star-forming galaxies, damped Lyα systems, blank sky, and the companions of quasars and damped Lyα systems. We suggest that, when Lyα emission is weak or absent, as is the case in most star-forming galaxies at low redshifts and in damped Lyα systems at high redshifts, the observed abundance of dust is sufficient to absorb most of the Lyα photons. On the other hand, when Lyα emission is strong, the presence of highly ionized species such as C IV and He II, large velocity widths, or nearby quasars indicate that much of the ionizing radiation may be supplied by active galactic nuclei. The null results of the many searches for Lyα emission from primeval galaxies are probably a consequence of the relatively brief periods in which galaxies are nearly dust-free and hence Lyα-bright.

Subject headings: galaxies: active — galaxies: evolution — galaxies: ISM — galaxies: stellar content — ultraviolet: galaxies

1. INTRODUCTION

The ionizing radiation from young stars in galaxies should lead to prominent Lyα emission by the recombination of hydrogen in the ambient interstellar medium. Partridge & Peebles (1967) suggested that this might be a valuable spectral signature of "primeval" galaxies at high redshifts because the strong and narrow Lyα line should be more readily visible than continuum radiation against the sky noise. Subsequent searches for Lyα emission from "blank sky" have all given null results, suggesting that young galaxies form stars slowly or in large volumes, or that the Lyα photons are absorbed by dust (Koo 1986; Baron & White 1987, and references therein). Recently, there has been renewed interest in searches for Lyα emission from young galaxies in the context of determining the star formation rates and sizes of the damped Lyα absorption systems. Furthermore, Lyα emission has now been detected at high redshifts in many radio galaxies and a few companions of quasars and damped Lyα systems. There is also a growing interest in the Lyα emission from nearby star-forming galaxies. Many of these observations have been interpreted in terms of the pioneering models by Partridge & Peebles (1967) and Meier (1976).

Our purpose here is to predict the Lyα emission from dust-free galaxies using more recent models of stellar population synthesis. We also describe some other processes that can affect Lyα emission in an attempt to provide a general framework for the interpretation of a wide variety of observations. This paper therefore complements our previous paper, which focused primarily on the attenuation of Lyα emission by dust in damped Lyα systems (Charlot & Fall 1991). In § 2, we review the Bruzual & Charlot (1993) models of stellar population synthesis, which are used to compute the ultraviolet spectra of galaxies. We then calculate in § 3 the Lyα emission from stellar populations with different star formation histories and initial mass functions (IMFs). In § 4, we discuss the possible contributions from supernova remnants and active galactic nuclei (AGNs), the dependence on viewing angle, and absorption by dust. Finally, in § 5, we consider the relevance of our results to the observations of and searches for Lyα emission from various kinds of galaxies at high and low redshifts. Throughout this paper, equivalent widths are taken to be positive for emission lines and are always quoted in the rest frame of the object in question.

2. POPULATION SYNTHESIS MODELS

We compute the spectral evolution of galaxies using the most recent version of the Bruzual & Charlot (1993) models of stellar population synthesis. These have solar metallicity and include all phases of stellar evolution from the zero-age main sequence to supernova explosion (for progenitors more massive than 8 $M_\odot$) or the end of the white dwarf cooling sequence (for less massive progenitors). Stars evolve along the tracks computed by Maeder & Meynet (1989), with the main-sequence lifetimes of intermediate-mass stars taken from Maeder & Meynet (1991). The models include mild over-

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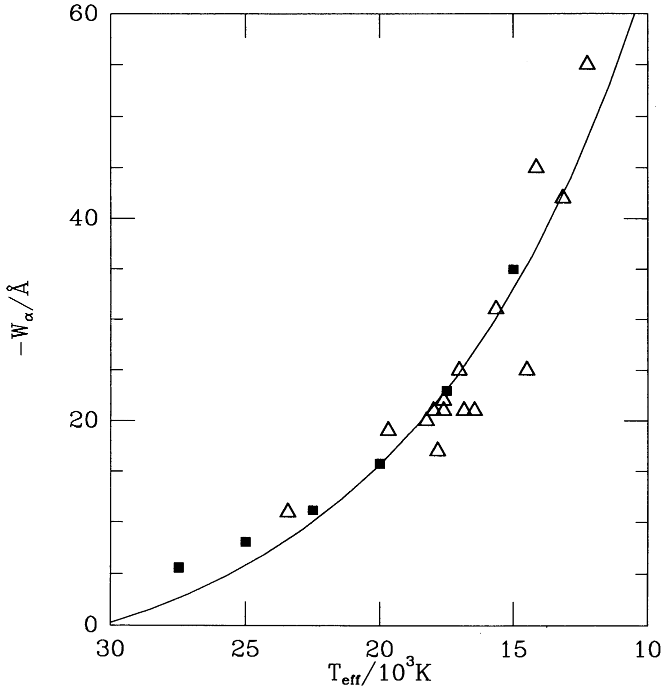

FIG. 1.—Stellar Lyα absorption equivalent width as a function of effective temperature. Open triangles are the observations by Savage & Panek (1974) of nearby Galactic stars with spectral types between B2.5 and B9. Filled squares are the predictions from non-LTE model atmospheres with log $g = 4$ by Mihalas (1972), as quoted by Savage & Panek. The solid line is the approximation given eq. (1).

shooting in the convective cores of stars more massive than 1.1 $M_\odot$, as indicated by various observations of Galactic star clusters. The central stars of planetary nebulae are assumed to be shrouded by their envelopes for 3×10^4 yr, the mean observed time for dispersal (Pottasch 1984). During this phase, dust in the envelopes absorbs all the ionizing radiation from the central stars and attenuates the radiation redward of the Lyman break. The main adjustable parameters in the population synthesis models are the star formation rate and the initial mass function. We compute a model spectrum at ages from 1×10^5 yr to 2×10^{10} yr in time steps that increase from 1.5×10^4 yr to 2.5×10^8 yr at late ages.

Most of the stellar spectra in the population synthesis models were taken directly from observations of Galactic stars at near-ultraviolet, optical, and near-infrared wavelengths and were extended into the far-ultraviolet using the Kurucz (1979) model atmospheres. The observed and model spectra were joined in the regions just blueward and redward of the Lyα line at $\lambda = 1216$ Å. The Lyα line itself was excluded because it is often contaminated by interstellar absorption or geocoronal emission and is not well represented by the Kurucz models (see below). The spectra of stars with effective temperatures in the range $40{,}000 < T_{\rm eff} \leq 50{,}000$ K were approximated at all wavelengths by the Kurucz models. The spectra of hotter stars (i.e., a few short-lived Wolf-Rayet stars and central stars of planetary nebulae) were approximated by unblanketed blackbodies, consistent with extensions of the Kurucz models to $T_{\rm eff} > 50{,}000$ K (Leitherer 1990). Nearly all the ionizing radiation from a stellar population with a normal IMF is produced by stars with $T_{\rm eff} \gtrsim 30{,}000$ K. Thus, the results presented in this paper rely heavily on the Kurucz model atmospheres.

The Kurucz (1979) models are static, plane-parallel atmospheres in local thermodynamic equilibrium (LTE) with line blanketing by about 10^6 atomic transitions. They have been extensively tested against models that include non-LTE effects, spherical geometry, atmospheric expansion, and stellar winds, but which are generally restricted to smaller ranges of temperature and include line blanketing by fewer atomic transitions (Mihalas 1972; Panagia 1973; Anderson 1985; Torres 1987; Longo et al. 1989; Leitherer 1990; Kudritzki et al. 1991; Schmutz, Leitherer, & Gruenwald 1992). These comparisons indicate that the Kurucz models underestimate the production of Lyman continuum photons by an amount that increases from a few percent at $T_{\rm eff} = 50{,}000$ K to about 25% at $T_{\rm eff} = 35{,}000$ K. Thus, for a stellar population with a normal IMF, we expect the overall discrepancy to be less than about 15%. At wavelengths redward of the Lyman break, the Kurucz models have been tested directly against *Voyager 1*, *Voyager 2*, *Copernicus*, *International Ultraviolet Explorer* (*IUE*), and *TD-1* observations of Galactic stars (Torres 1987; Longo et al. 1989, and references therein). The agreement between the model and observed spectra is also generally better than 15%. This level of accuracy is sufficient for our purposes.

The absorption of Lyα photons in stellar atmospheres involves non-LTE effects and must therefore be included explicitly in the population synthesis models. We adopt the following expression for the Lyα equivalent width in stars of different effective temperatures:

$$W_\alpha/\text{Å} = 7\text{–}220 \exp(-T_{\rm eff}/8800\ \text{K}) \quad \text{for } 8000 < T_{\rm eff} < 30{,}000\ \text{K}\,, \qquad (1a)$$

$$W_\alpha/\text{Å} = 0 \qquad \text{otherwise}\,. \qquad (1b)$$

As Figure 1 shows, this is a good approximation to the observations of nearby Galactic B stars by Savage & Panek (1974) and the predictions from non-LTE model atmospheres with surface gravity log $g = 4$ by Mihalas (1972). Our expression for W_α is similar to the one proposed by Valls-Gabaud (1993) except that it is forced to zero at $T_{\rm eff} = 30{,}000$ K. The reason for this is that, in hotter stars, the Lyα line is produced in radiatively driven winds rather than in the stellar photospheres. In fact, non-LTE models of O-star winds have Lyα lines with P Cygni profiles in which the emission and absorption components are of nearly equal strength and therefore lead to net equivalent widths of only a few angstroms (Klein & Castor 1978; Leitherer & Schmutz 1993). We also neglect absorption in stars cooler than 8000 K (i.e., spectral types later than A7) because they show weak Lyα emission from their chromospheres (Landsmann & Simon 1993). This, however, has almost no effect on our results since such cool stars never dominate the integrated ultraviolet spectra.

3. EMISSION FROM STELLAR POPULATIONS

In this section, we compute the Lyα emission from galaxies under the following "minimal" assumptions. We assume that circumstellar H II regions are the only sources of Lyα photons and that the column density of the ambient H I is large enough that case B recombination applies ($N_{\rm H\,I} \gtrsim 10^{17}$ cm^{-2}) but otherwise ignore the effects of the interstellar medium on the transfer of Lyα photons. The fraction of ionizing photons that are converted into Lyα photons then depends weakly on the temperature of the gas and is 0.68 for 10^4 K (Spitzer 1978, Table 9.1). We also assume that stars form with a power-law initial mass function $\phi(m) \propto m^{-1-x}$ [defined such that $\phi(m)dm$ is the number of stars born with masses between m and $m + dm$]. The slope of the IMF is taken to be $x = 0.5$, 1.5, or 2.5. For reference, the Salpeter IMF has $x = 1.35$ and the Scalo (1986) IMF has $x \approx 1.3$ for $m \gtrsim 3\ M_\odot$. We take the upper cutoff of the IMF to be $m_U = 40$, 80, or 120 $M_\odot$. The lower cutoff, which is fixed at $m_L = 0.1\ M_\odot$, has hardly any effect on the Lyα emission.

We consider two extreme histories of star formation in the model galaxies: a burst, generated by an exponentially declining star formation rate with a time scale of 10^7 yr, and a constant star formation rate. In the first case, a total of $10^{11}\ M_\odot$ of stars is produced during the burst. We have chosen a time scale of 10^7 yr because it is unlikely that star formation could be synchronized across even a small galaxy on a shorter time scale. In the second case, the star formation rate is assumed to be 6.7 $M_\odot$ yr^{-1}, which produces $10^{11}\ M_\odot$ of stars in 15 Gyr. The Lyα emission for any other star formation rate can be scaled directly from the results presented here. A burst of star formation might be appropriate for a whole elliptical galaxy or for an isolated region of a spiral or irregular galaxy. However, in the case of an elliptical galaxy, our estimate of the Lyα emission would be too high if all the H I were consumed by star formation or expelled in a galactic wind because the ionizing radiation would then escape without producing Lyα photons. Most spiral galaxies have present star formation rates within a factor of a few of their past-averaged rates (Kennicutt 1983). Thus, a constant rate of star formation should be appropriate for a typical spiral galaxy, even though this may require late infall of gas.

Figure 2 shows the model spectrum of a burst stellar population at various ages for the IMF with $x = 1.5$ and $m_U = 80\ M_\odot$. The evolution of the Lyα luminosity L_α and equivalent width W_α of this model are shown in Figure 3. During the burst, the Lyα emission is strong but declines rapidly as the most massive stars complete their evolution. Cooler stars with atmospheric absorption then account for most of the ultraviolet radiation, and the Lyα equivalent width of the stellar population becomes negative after about 4×10^7 yr. In this phase, the central stars of planetary nebulae are shrouded by their envelopes and therefore do not contribute to the Lyα emission. However, once the central stars begin to outlive their envelopes, the Lyα equivalent width of the stellar population increases abruptly to more than 200 Å at about 10^9 yr. The rapid rise in W_α is a consequence of the strong dependence of the lifetimes of the central stars on their masses and is not an artifact of the simplifying assumption that all planetary nebulae have the same dispersal time. The corresponding feature in L_α is weaker because the central stars of planetary nebulae are relatively faint at this stage.

Figures 3 and 4 show the effects of the slope and upper cutoff of the IMF on the Lyα luminosity and equivalent width of burst stellar populations. As the IMF steepens, the proportion of massive stars decreases, and both the Lyα luminosity and equivalent width decrease. Figure 3 shows that a change in x from 0.5 to 2.5 reduces L_α by three orders of magnitude and W_α from 150 to 30 Å at an age of 2×10^7 yr. The Lyα luminosity also depends on the slope of the IMF after 10^9 yr, when the central stars of planetary nebulae dominate the ionizing radiation. In this phase, however, the Lyα equivalent width is not

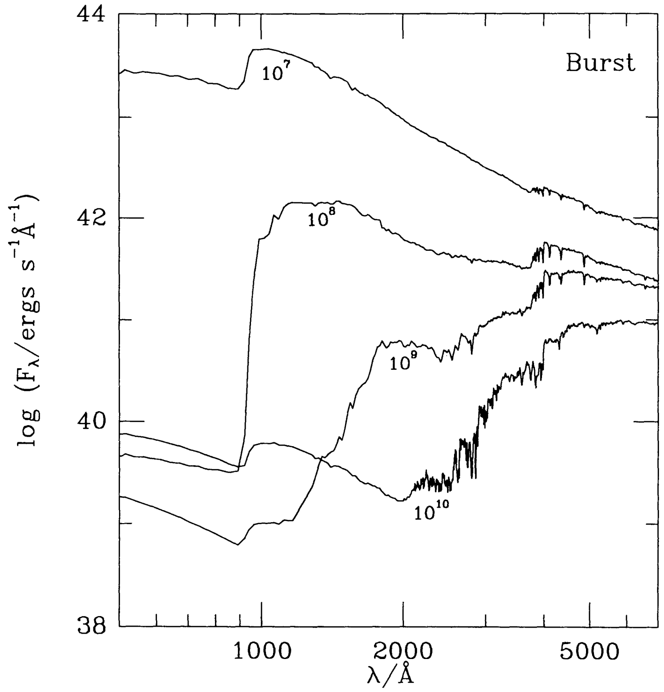

FIG. 2.—Spectral evolution of a burst stellar population with an exponentially declining star formation rate of time scale 10^7 yr. The age (in yr) is indicated next to the spectra. The IMF has the slope $x = 1.5$ and the upper cutoff $m_U = 80\ M_\odot$. The models have solar metallicity, and the flux is normalized to a total of $10^{11}\ M_\odot$ of stars formed during the burst.

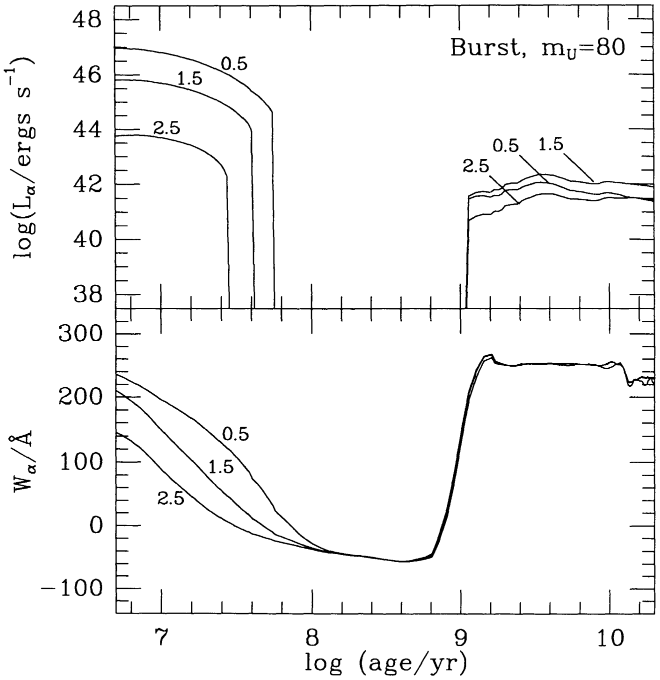

FIG. 3.—Evolution of the Lyα luminosity and equivalent width of a burst stellar population for different values of the IMF slope x (indicated next to the curves), with fixed upper cutoff m_U. The luminosity is normalized to $10^{11}\ M_\odot$ of stars formed during the burst.

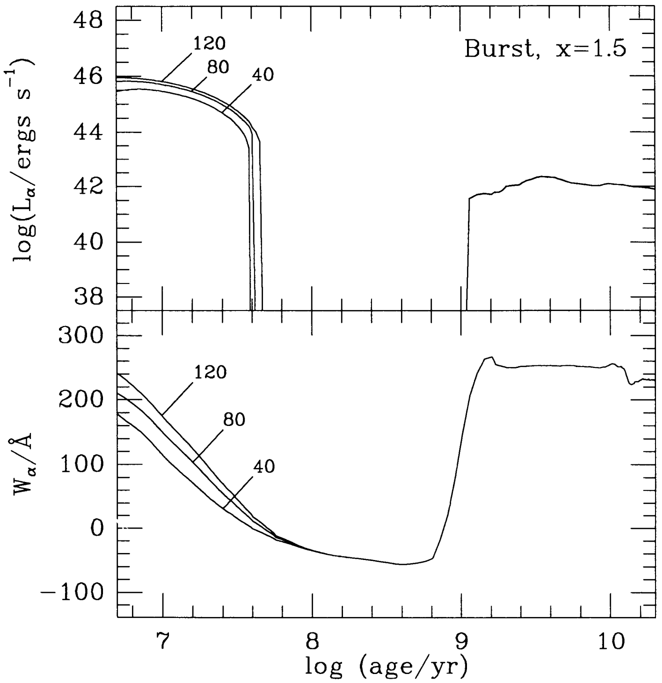

FIG. 4.—Evolution of the Lyα luminosity and equivalent width of a burst stellar population for different values of the IMF upper cutoff m_U (indicated next to the curves), with fixed slope x. The luminosity is normalized to 10^{11} $M_\odot$ of stars formed during the burst.

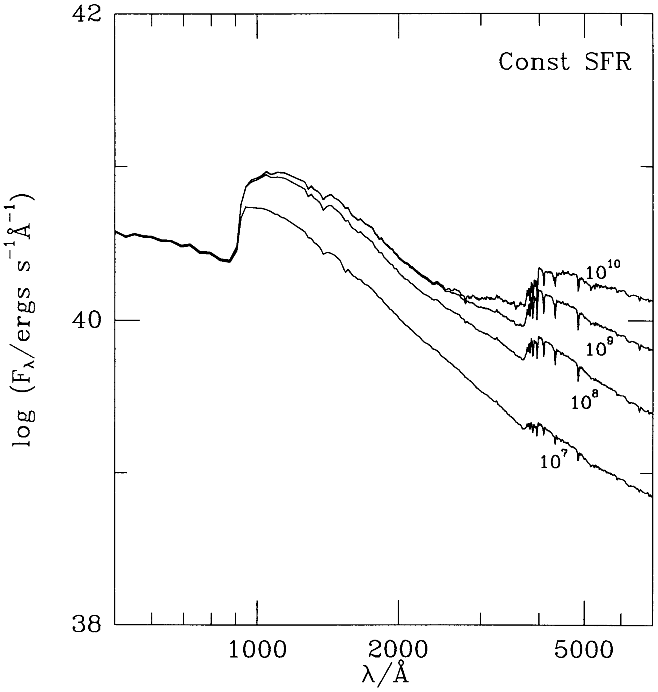

FIG. 5.—Spectral evolution of a stellar population with a constant star formation rate. The age (in yr) is indicated next to the spectra. The IMF has the slope $x = 1.5$ and the upper cutoff $m_U = 80$ $M_\odot$. The models have solar metallicity, and the flux is normalized to a star formation rate of 6.7 $M_\odot$ yr^{-1}, which corresponds to 10^{11} $M_\odot$ of stars formed in 15 Gyr.

sensitive to the slope of the IMF because the cooling tracks of the central stars are then nearly independent of mass. The Lyα luminosity and equivalent width depend only weakly on the upper cutoff of the IMF. The reason for this is that, near the cutoff, more massive stars have higher luminosities but shorter lifetimes and similar temperatures; hence they produce roughly the same number of ionizing photons. For example, a 120 $M_\odot$ star on the main sequence is about seven times brighter than a 40 $M_\odot$ star but lives half as long, while its effective temperature is only 20% higher.

Figure 5 shows the spectral evolution of a stellar population with a constant star formation rate and the IMF with $x = 1.5$ and $m_U = 80$ $M_\odot$, and Figure 6 shows the corresponding evolution of the Lyα luminosity and equivalent width. The Lyα luminosity remains roughly constant since it is dominated by the massive stars that are continuously replenished on the main sequence. The central stars of planetary nebulae make a negligible contribution at all ages because they are so much fainter than main-sequence stars. Initially, the Lyα equivalent width decreases as the less-massive, longer-lived stars that contribute to the continuum around 1200 Å accumulate on the main sequence. However, after 10^8 yr, when a steady population of O and B stars is reached, W_α varies slowly and remains positive. Figures 6 and 7 show how the Lyα luminosity and equivalent width depend on the slope and upper cutoff of the IMF for stellar populations with constant star formation rates. As with burst populations, L_α and W_α are sensitive to x but not to m_U. In fact, the Lyα equivalent width depends even more strongly on the slope of the IMF than for a burst, decreasing at an age of 10^8 yr from 170 to 20 Å as x increases from 0.5 to 2.5.

We find that the Lyα equivalent width of a stellar population, computed here for the two extreme cases of a burst and

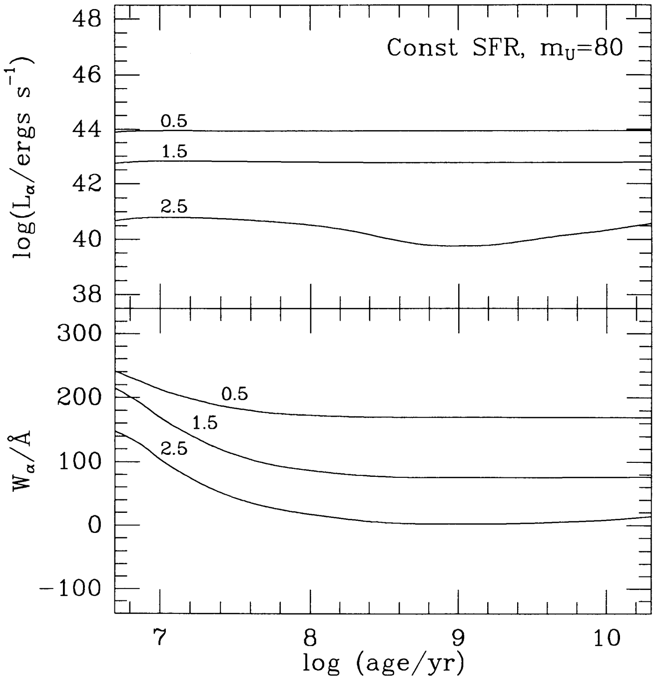

FIG. 6.—Evolution of the Lyα luminosity and equivalent width of a stellar population with a constant star formation rate for different values of the IMF slope x (indicated next to the curves), with fixed upper cutoff m_U. The luminosity is normalized to 10^{11} $M_\odot$ of stars formed in 15 Gyr.

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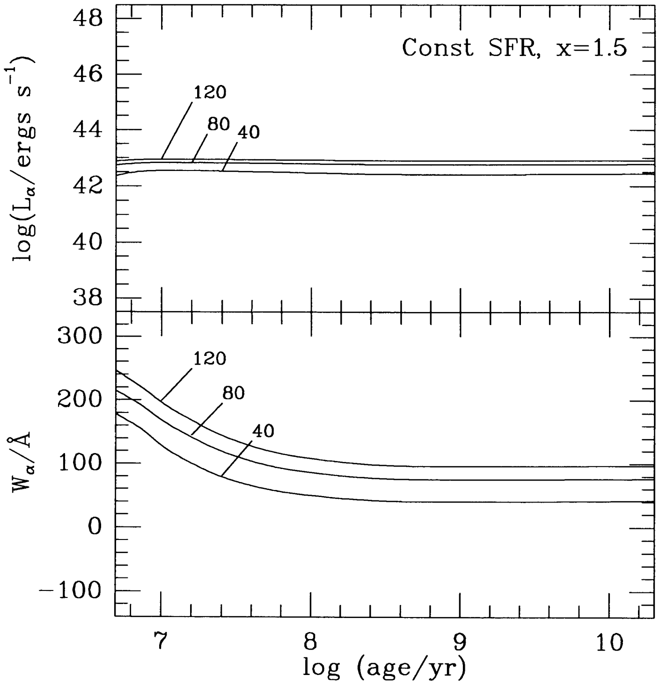

FIG. 7.—Evolution of the Lyα luminosity and equivalent width of a stellar population with a constant star formation rate for different values of the IMF upper cutoff m_U (indicated next to the curves), with fixed slope x. The luminosity is normalized to 10^{11} $M_\odot$ of stars formed in 15 Gyr.

a constant rate of star formation, ranges between 100 and 200 Å at early ages (from a few times 10^6 yr to a few times 10^7 yr) for an IMF similar to that in the solar neighborhood. Comparisons between the low- and high-metallicity models of Maeder & Meynet (1989, 1991) and Kurucz (1979) indicate that the Lyα luminosity would be about 15% higher if the abundances of heavy elements were reduced to 10% of the solar values. The Lyα equivalent width, however, would be even less affected since metal-poor stars also have stronger continua near Lyα. Our models have Lyα equivalent widths significantly higher than the value $W_\alpha \approx 70$ Å predicted by Partridge & Peebles (1967) and Meier (1976). Partridge & Peebles approximated the ultraviolet spectrum of a young galaxy by a single blackbody with a temperature of only 30,000 K, modified blueward of the Lyman break to account for absorption in stellar atmospheres. Meier used Tinsley's (1972) population synthesis models, which did not include convective overshooting on the main sequence. Thus, the lifetimes of massive stars, and hence their supply of ionizing radiation, were significantly smaller than in the models used here.

4. OTHER EMISSION AND ABSORPTION PROCESSES

In this section, we describe several other factors that can affect the observed Lyα emission from galaxies. These include the contributions from supernova remnants and active galactic nuclei, the orientation of a galaxy, and absorption by dust. We first consider supernova remnants. Shull & Silk (1979) have computed the time-averaged, Lyα luminosity of a population of Type II supernova remnants using a radiative-shock code with low metallicities. The result is $L_\alpha = 3 \times 10^{43} n_{\mathrm{H}}^{-1/2} E_0^{3/4} \dot{N}_{\mathrm{SN}}$ ergs s^{-1}, where n_{H} is the ambient density in cm^{-3}, E_0 the typical supernova energy in units of 10^{51} ergs, and $\dot{N}_{\mathrm{SN}}$ is the number of supernovae per year. This expression includes both the Lyα photons emitted directly by the cool shells and those emitted in the recombination of hydrogen surrounding the remnants and ionized by X-ray and ultraviolet photons from the hot interiors. A comparison with the radiative-shock model by Shull & McKee (1979) indicates that the coefficient in the expression would be about 40% lower for solar metallicity. Shull & Silk neglected the adiabatic phase in the evolution of the supernova remnants. The calculations by Chevalier (1974) for $n_{\mathrm{H}} = 1$ cm^{-3} indicate that the inclusion of this phase would increase the Lyα luminosity by only about 10%.

We have used the Shull & Silk (1979) formula to estimate the contribution of supernova remnants to the Lyα emission from model galaxies with burst stellar populations and constant star formation rates. In these calculations, we assume that all stars more massive than 8 $M_\odot$ explode as Type II supernovae and neglect Type I supernovae, which should be a good approximation for the first few times 10^9 yr (e.g., Matteucci & Greggio 1986). For $n_{\mathrm{H}} = 1$ cm^{-3}, roughly the mean density in the interstellar medium of the Milky Way, the contribution by supernova remnants to the Lyα emission is always less than the contribution by stars (by factors of 25, 10, and 2.5, respectively, when the slope of the IMF is $x = 0.5$, 1.5, and 2.5). Since supernovae are expected to occur preferentially in regions with densities higher than the mean, and since their contribution to the Lyα emission scales with the density as $n_{\mathrm{H}}^{-1/2}$, they can probably be neglected in most cases. Bithell (1991) has reached a different conclusion, but this appears to be based on an assumption that the supernovae in protogalaxies would occur in regions of very low density. Finally, we note that Lyα photons will also be produced by the stellar-wind bubbles preceding the supernovae, an effect that has not yet been studied in detail.

AGNs are another potential source of ionizing radiation in galaxies. We assume for simplicity that the spectrum of an AGN can be approximated by a power law, $f_\nu \propto \nu^{-\alpha}$, with an index blueward of Lyα in the range $1 \lesssim \alpha \lesssim 2$ (O'Brien, Gondhalekar, & Wilson 1988). If we also assume that the AGN is completely surrounded by H I, that case B recombination applies, and that absorption by dust is negligible, then the Lyα equivalent width is given by

$$W_\alpha = 0.68 \frac{c}{\nu_\alpha f_c} \int_{\nu_{\mathrm{L}}}^{\infty} d\nu f_\nu / \nu \approx 827 \alpha^{-1} (3/4)^\alpha \text{ Å} . \qquad (2)$$

Here c is the speed of light, f_c is the flux in the continuum near Lyα, and ν_{L} and ν_α are the frequencies at the Lyman limit and at Lyα. Equation (2) yields $W_\alpha \approx 600$ Å for $\alpha = 1$ and $W_\alpha \approx 200$ Å for $\alpha = 2$. Thus, in principle, AGNs can produce higher Lyα equivalent widths than stellar populations. Most bright quasars, however, are observed to have $50 \lesssim W_\alpha \lesssim 150$ Å (Schmidt, Schneider, & Gunn 1986; Baldwin, Wampler, & Gaskell 1989). This could reflect a partial covering of the AGNs by H I clouds in the broad-line regions of the quasars or some attenuation of the Lyα emission by dust. The situation is further complicated by the possibility that the covering factor and attenuation could depend on the angles at which the AGNs are observed.

Fortunately, the presence of an AGN in a galaxy is usually revealed by other readily identifiable signatures. These include strong emission lines of highly ionized species such as C IV ($\lambda = 1549$ Å) and He II ($\lambda = 1640$ Å), which are generally not produced by the softer spectra of stellar populations (van

Breugel & McCarthy 1989; McCarthy et al. 1990). Furthermore, photoionization by AGNs produces spectra in which the emission lines of different ionization states of the same element have roughly equal strengths (e.g., C II, C III, and C IV). The broad emission lines of most AGNs also have velocity widths (FWHMs of several thousand km s^{-1}) that are several times larger than those expected from the virial motions within galaxies (FWHMs less than about 1000 km s^{-1}, corresponding to line-of-sight velocity dispersions less than about 400 km s^{-1}). If dust is present, the higher velocity widths associated with AGNs should allow more photons to escape in the wings of the Lyα line (see eq. [3] below). This is another reason for expecting strong Lyα emission from galaxies with AGNs.

The Lyα photons produced in galaxies will suffer a large number of resonant scatterings in the ambient neutral atomic hydrogen. In the absence of dust, this would lead to no net enhancement or decrement of the angle-averaged Lyα emission from a galaxy because each Lyα photon absorbed by the H I would be reemitted as a new Lyα photon. Similarly, the total Lyα emission from a sample of randomly-oriented galaxies cannot be affected by resonant scattering alone. However, since the Lyα line is emitted more isotropically than the continuum, the Lyα equivalent width of an individual galaxy will decrease as it is viewed more nearly edge-on. In the idealized case of a plane-parallel slab, the Lyα intensity follows a "limb-darkening" law of the form[2] $g(\mu) = (18/13)(1 + 2\mu/3)$, while the continuum intensity varies as μ^{-1}, where μ is the cosine of the angle to the normal. Thus, the Lyα equivalent width varies as $W_\alpha(\mu) = \mu g(\mu)\langle W_\alpha \rangle$, where $\langle W_\alpha \rangle$ is the angle-averaged value. This gives $W_\alpha(\mu)/\langle W_\alpha \rangle = 2.3$, 1.9, 0.9, and 0, respectively, for $\cos^{-1} \mu = 0°, 30°, 60°$, and 90°.

The resonant scattering of Lyα photons by H I in the interstellar medium of a galaxy also increases enormously their chances of absorption by dust grains with respect to continuum photons. The attenuation of Lyα emission is expected to be important when the dimensionless dust-to-gas ratio, defined in terms of the extinction optical depth in the B band by $k \equiv 10^{21}(\tau_B/N_{\rm H\,I})\ \mathrm{cm}^{-2}$, exceeds the critical value

$$k_{\rm crit} \approx 1 \times 10^{-2}(N_{\rm H\,I\perp}/10^{21}\ \mathrm{cm}^{-2})^{-4/3}(\sigma_V/10\ \mathrm{km\ s}^{-1})^{2/3} \tag{3}$$

(which follows from eq. [8] of Charlot & Fall 1991 with $\delta \approx 2$). In this expression, $N_{\rm H\,I\perp}$ and σ_V are the face-on column density and line-of-sight velocity dispersion of the neutral atomic hydrogen. For reference, the dust-to-gas ratio in the Milky Way and the Large and Small Magellanic Clouds are, respectively, $k \approx 0.8$, $k \approx 0.2$, and $k \approx 0.05$ (Bohlin, Savage, & Drake 1978; Koornneef 1982; Lequeux et al. 1984). The face-on H I column densities within the optically visible regions of most spiral galaxies lie in the range $10^{20} \lesssim N_{\rm H\,I\perp} \lesssim 10^{21}$ cm^{-2} (Warmels 1988a, b). The lower end of this range is also roughly the threshold for star formation suggested by Kennicutt (1989). Thus, according to equation (3), we expect some attenuation of the Lyα emission unless the dust-to-gas ratio is much smaller than the value in the Milky Way.

Unfortunately, the attenuation of Lyα emission by dust also depends sensitively on the structure of the interstellar medium in a galaxy. Even in the idealized case of a homogeneous interstellar medium with static, plane-parallel geometry, the attenuation is more severe if the sources of Lyα photons are all confined to the midplane than if they are distributed in the same way as the gas and dust (Hummer & Kunasz 1980; Neufeld 1990). In fact, the attenuation differs in these situations by more than an order of magnitude for $k \gtrsim 30k_{\rm crit}$ (see eq. [9] and Fig. 3 of Charlot & Fall 1991). The range of attenuation can be even greater when the interstellar medium has a multiple-phase structure. In this case, the transfer of Lyα photons depends largely on the topology of the interfaces between H I and H II regions. If all the H II regions are isolated from each other, the surrounding H I will repeatedly scatter the Lyα photons back into the H II regions, where they will eventually be absorbed by dust (Spitzer 1978, § 5.1.c). Very few Lyα photons will then escape from the galaxy. If, instead, all the H II regions are connected to each other and to the outside surface, the embedded H I clouds will scatter the Lyα photons throughout the galaxy, and many more of them will escape (Neufeld 1991). As a result of these complications, it is nearly impossible to deduce star formation rates from the observed Lyα emission.

5. DISCUSSION

We can summarize much of the preceding material as follows: (1) for $W_\alpha \gtrsim 400$ Å, there is no doubt that an AGN must account for most of the Lyα emission. (2) For 200 Å $\lesssim W_\alpha \lesssim 400$ Å, the main source of Lyα photons must also be an AGN but unless it has a relatively steep spectrum, absorption by dust could play a role. (3) For 100 Å $\lesssim W_\alpha \lesssim 200$ Å, stars alone could account for all the Lyα emission if there were no attenuation. However, the stellar population must then be younger than about 10^8 yr, or its IMF must be enriched in massive stars with respect to that in the solar neighborhood. Equivalent widths between 100 and 200 Å can also be produced by an AGN with substantial attenuation. (4) For $W_\alpha \lesssim 100$ Å, the Lyα emission can have several different origins. It could either be a stellar population older than about 10^8 yr with a normal IMF, or a younger one with some attenuation or with an IMF deficient in massive stars, or an AGN with severe attenuation. (5) For $W_\alpha \lesssim 0$ Å, the galaxy could be in a special evolutionary phase, between a few times 10^7 yr and 10^9 yr after a burst of star formation, when the ultraviolet spectrum is dominated by late-B and A stars with strong atmospheric Lyα absorption.[3] We emphasize that the regimes summarized here pertain to angle-averaged Lyα equivalent widths and that, as a result of the dependence on orientation, the observed value of W_α for any particular galaxy may be harder to interpret. We now discuss the Lyα emission from various kinds of galaxies with these points in mind.

There have been several studies of the Lyα emission from galaxies that are near enough to be observed with *IUE* but have redshifts high enough to avoid contamination by geocoronal Lyα emission (Meier & Terlevich 1981; Hartmann, Huchra, & Geller 1984; Deharveng, Joubert, & Kunth 1986; Hartmann et al. 1988; Calzetti & Kinney 1992; Terlevich et al.

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[2] The limb-darkening law adopted here has the same dependence on angle as the one proposed by Charlot & Fall (1991) but is normalized correctly to $\int_0^1 d\mu\, \mu g(\mu) = 1$. This normalization reduces the star formation rates in Table 1 of Charlot & Fall (1991) by a factor of 1.8 but does not alter the main conclusions of that paper.

[3] Chen & Neufeld (1993) point out that the Lyα equivalent width of a galaxy can be negative even if the star formation rate is constant. The reason for this is that dust not only attenuates the Lyα emission from H II regions but also the stellar radiation at Lyα. Under some circumstances, the net result can be an absorption feature in the integrated spectrum. The equivalent width of the feature depends on the dust-to-gas ratio and the H I column density in the galaxy, with $W_\alpha \approx -10$ Å obtained for some combinations of k and $N_{\rm H\,I}$.

1993). The galaxies were specifically chosen because they showed signs of vigorous star formation, i.e., very blue colors, prominent H II regions, and so forth. Most of the observed Lyα luminosities lie in the range $3 \times 10^{40} \lesssim h^2 L_\alpha \lesssim 5 \times 10^{41}$ ergs s^{-1}, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. Our models indicate that, if there were no attenuation of the Lyα emission and the IMF were normal, the star formation rates would then be very low: $0.03 \lesssim h^2 \dot{M}_S \lesssim 0.5$ $M_\odot$ yr^{-1} (either during a burst or with a constant rate of star formation). For comparison, the current star formation rate in the Milky Way is roughly 5 $M_\odot$ yr^{-1} (Smith, Biermann, & Mezger 1978). The observed Lyα equivalent widths of the nearby star-forming galaxies lie in the range $-20 \lesssim W_\alpha \lesssim 120$ Å, but most of them have $W_\alpha \lesssim 30$ Å. The weak Lyα emission could be explained without attenuation if the galaxies were being observed after a burst of star formation (Valls-Gabaud 1993). This, however, would contradict the many signs of current star formation in the galaxies.

The most likely explanation for the weak Lyα emission from the nearby star-forming galaxies is attenuation by dust (Meier & Terlevich 1981; Hartmann, Huchra, & Geller 1984). The gas-phase abundances of oxygen in these galaxies lie in the range $-1.1 \lesssim$ [O/H] $\lesssim 0.4$, and the observed H I column densities lie in the range $2 \times 10^{20} \lesssim N_{\rm H\,I} \lesssim 4 \times 10^{21}$ cm^{-2}. The dust-to-gas ratios are not known, although it is probably safe to assume that they correlate with [O/H]. As Figure 8 shows, there is a significant anticorrelation between the Lyα equivalent widths and the abundances of oxygen, such that the galaxies with $W_\alpha \lesssim 30$ Å all have [O/H] $\gtrsim -0.8$. This is consistent with the condition $k \gtrsim k_{\rm crit}$ and hence attenuation by dust (for plausible relations between [O/H] and k). The advantages of using the Lyα equivalent widths, rather than the Lyα/Hβ ratios, in such comparisons are that W_α is independent of the extinction curve of the dust and can be measured with a single ultraviolet spectrograph. Calzetti & Kinney (1992) and Valls-Gabaud (1993) note that the dereddened Lyα/Hβ ratios for some nearby star-forming galaxies are consistent with case B recombination (for some forms of the extinction curve) and conclude from this that the Lyα photons are not resonantly scattered by H I and preferentially absorbed by dust. This seems unlikely, however, in view of the anticorrelation between W_α and [O/H] shown in Figure 8.

The best candidates for ordinary galactic disks at high redshifts are the damped Lyα systems. These objects, discovered as strong absorption features in the spectra of background quasars, have redshifts in the range $2 \lesssim z \lesssim 3$ and observed H I column densities in the range $2 \times 10^{20} \lesssim N_{\rm H\,I} \lesssim 6 \times 10^{21}$ cm^{-2} (Lanzetta et al. 1991). There have been several searches for Lyα emission from the damped Lyα systems (Foltz, Chaffee, & Weymann 1986; Smith et al. 1989; Wolfe 1989; Deharveng, Buat, & Bowyer 1990; Hunstead, Pettini, & Fletcher 1990; Pettini, Boksenberg, & Hunstead 1990; Lowenthal et al. 1991; Wolfe et al. 1992; Møller & Warren 1993). These have led to only a few tentative detections near the limiting intensity of the deepest searches: $I_\alpha \lesssim 10^{-17}$ ergs s^{-1} cm^{-2} arcsec^{-2}. The corresponding limit on the Lyα luminosity for an object extending over 2×2 arcsec^2 at $z = 2.5$ (i.e., of roughly the size of the Milky Way) is $L_\alpha \lesssim 5 \times 10^{41}$ h^{-2} ergs s^{-1} (here and throughout this paper we adopt $q_0 = 0.5$). In the absence of attenuation, the limit on the star formation rate would be $\dot{M}_S \lesssim 0.5$ h^{-2} $M_\odot$ yr^{-1}. However, dust has been detected in the damped Lyα systems using two different methods: the reddening of background quasars (Fall, Pei, & McMahon 1989; Pei, Fall, & Bechtold 1991) and the depletion of Cr relative to Zn (Meyer & Roth 1990; Pettini, Boksenberg, & Hunstead 1990; Bergeron & Petitjean 1991; Pettini et al. 1993). Both methods indicate that the typical dust-to-gas ratio in the damped Lyα systems is roughly 10% of that in the Milky Way, although there may be a large dispersion around this value. Equation (3) then implies that the attenuation of Lyα emission by dust should be important. As discussed in § 4, the exact attenuation is highly uncertain, and the limits on the Lyα emission from the damped Lyα systems are consistent with star formation rates more than an order of magnitude higher than the value given above for the dust-free case (see Charlot & Fall 1991 for a more complete analysis).

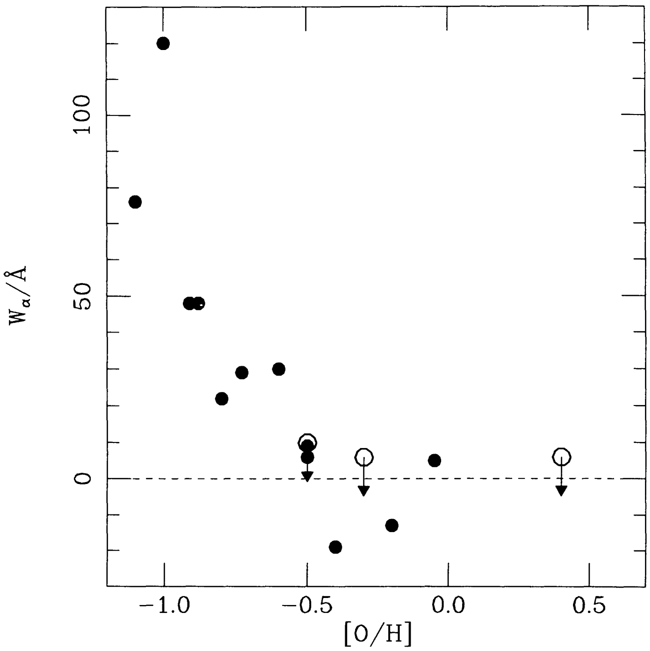

FIG. 8.—Observed Lyα equivalent width as a function of oxygen abundance in nearby star-forming galaxies (Meier & Terlevich 1981; Hartmann, Huchra, & Geller 1984; Deharveng, Joubert, & Kunth 1986; Hartmann et al. 1988; Calzetti & Kinney 1992; Terlevich et al. 1993). Negative equivalent widths indicate absorption.

There have also been several searches for Lyα emission from galaxies at high redshifts in blank-sky surveys, using narrowband imaging or long-slit spectroscopy (Koo 1986 and references therein; Cowie 1987; Pritchet & Hartwick 1987, 1990; Lowenthal et al. 1990; Djorgovski, Thompson, & Smith 1993). The first technique samples a large solid angle (a few arcmin^2) but only a small interval of redshift ($\Delta z \lesssim 0.1$), while the second samples a small solid angle (typically < 0.1 arcmin^2) but a large interval of redshift ($\Delta z \approx 1.5$). Several searches covering much of the redshift range $2 \lesssim z \lesssim 6$ have revealed no convincing Lyα emission down to a limiting intensity of $I_\alpha \lesssim 10^{-17}$ ergs s^{-1} cm^{-2} arcsec^{-2}. This is similar to the limits reached in the searches for Lyα emission from the damped Lyα systems and therefore has similar implications for the star formation rates. In fact, since the damped Lyα systems contain most of the neutral atomic hydrogen in the universe at redshifts in the range $2 \lesssim z \lesssim 3$, they are also the most likely sites of star formation in blank-sky regions. Thus, it seems plausible that the weak or absent Lyα emission from the damped Lyα systems and blank sky has a common explanation in terms of attenuation by dust.

Strong Lyα emission has been observed in some galaxies at high redshifts. In particular, radio galaxies often have Lyα equivalent widths in the range $100 \lesssim W_\alpha \lesssim 600$ Å (Chambers & Miley 1989; Spinrad 1989; McCarthy et al. 1991). Much of the ionizing radiation must therefore come from AGNs, as confirmed by the strong emission lines of highly ionized species and the large velocity widths of the Lyα line. Several spatially resolved companions of high-redshift quasars have also been found with strong Lyα emission (Djorgovski et al. 1987; Heckman et al. 1991; Hu et al. 1991; Steidel, Sargent, & Dickinson 1991; Møller & Warren 1993). Most of these objects are close enough to the quasars to account for much or all of the observed Lyα emission. Recently, Lyα emission has been detected in two spatially resolved companions of damped Lyα systems: G PHL 957 (Lowenthal et al. 1991) and G2 0000−2619 (Macchetto et al. 1993). The first has $L_\alpha \approx 5 \times 10^{42}\ h^{-2}$ ergs s^{-1} and $W_\alpha \approx 140$ Å, while the second has $L_\alpha \approx 2 \times 10^{43}\ h^{-2}$ ergs s^{-1} and $W_\alpha \approx 160$ Å. It is possible that the Lyα emission from these objects is produced by young stellar populations (i.e., ages less than 2×10^7 yr) with no attenuation by dust and star formation rates of $5\ h^{-2}\ M_\odot$ yr^{-1} (G PHL 957) and $20\ h^{-2}\ M_\odot$ yr^{-1} (G2 0000−2619). However, the strong C IV and He II lines in G PHL 957 indicate that it may have an AGN.

The preceding examples are all consistent with our expectation that strong Lyα emission requires either a low abundance of dust or an AGN. Thus, we can understand why few, if any, "normal" galaxies have been found in the searches for Lyα emission at high redshifts. In fact, it might be easier to detect the continuum or Balmer-line emission from such galaxies. The hope has always been that the searches for Lyα emission at high redshifts would reveal a population of "primeval" galaxies, in which the abundances of heavy elements and hence dust were low enough that most of the Lyα photons could escape. Such a population must exist at some redshifts. In theories based on hierarchical clustering, galaxies are predicted to form relatively recently and over a wider range of redshifts (e.g., Baron & White 1987). Since the Lyα emission is attenuated when the dust-to-gas ratio exceeds 1%–10% of the value in the Milky Way, a typical galaxy probably spends only the first few percent of its lifetime in a Lyα-bright phase (and even less if the initial rate of chemical enrichment is higher than the average rate). We therefore expect primeval galaxies, as defined above, to be relatively rare at most redshifts, consistent with the null results of all searches to date. However, these arguments are not conclusive, and additional searches for Lyα emission at other redshifts and with higher sensitivity might be worthwhile.

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