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GALAXY FORMATION AND THE ORIGIN OF THE IONIZING FLUX AT LARGE REDSHIFT

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ABSTRACT

The absence of any continuous Lyα opacity from the intergalactic medium at $z = 3$–4.5 can be understood if a significant population of star-forming galaxies is present at these redshifts. We show that such galaxies can be present within the galaxy populations at $22 < B < 27$. We analyze theoretically the expected ionization produced during galaxy formation in terms of highly model-independent metal production arguments and conclude that (if such galaxies are dust-free and transparent to ionizing photons) then at least $4(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^3$% of galaxy formation would have to have occurred in this redshift range. Finally we note that some part of the "blue" or "flat-spectrum" galaxy population that appears in galaxy counts at $B > 23$ could be a prime candidate for the producer of the ionizing flux at $z = 3$. We speculate that these objects may also be the source of the diffuse X-ray background and also suggest that the ionized surfaces of the damped Lyα clouds may be close to detectability.

Subject headings: cosmology — early universe — galaxies: formation

I. INTRODUCTION

The absence of any significant continuous Lyα absorption from the intergalactic medium (the Gunn-Peterson effect) in even the most distant quasars (e.g., Steidel and Sargent 1988) has reopened the question of the origin of the ionizing flux. While the time scale for full recombination in the intergalactic medium (IGM) is longer than the cosmological time scale at these redshifts, the recombination time to violate the neutral hydrogen constraints [$\alpha^{-1} n_{\rm H}/n_e^2 \approx 10^{16}(1+z)^{-5}h^{-3}(\Omega_B/0.03)^{-2}\tau(z)$ s; see eq. (1)] is always very much shorter. The Gunn-Peterson effect therefore cannot be a relic of earlier ionization but requires a current and substantial ionizing flux. Though quasars can account for the required ionization of any reasonable IGM at low redshifts, at these higher redshifts they are only a marginal source (Shapiro and Giroux 1987; Donahue and Shull 1987). Recognizing this, Bechtold *et al.* (1987) have discussed the alternative possibility that the ionizing flux results from star formation in galaxies at or just beyond these redshifts. They concluded that this could be a possible source of the ionizing flux, but that the hypothesis suffers from a lack of any observational evidence.

The problem of determining the ionization source of the IGM at high redshift can be addressed rather directly with ground-based observations since, at $z = 3$–5, the Lyman-continuum edge shifts to the wavelength range 3600–5400 Å at the present epoch, and so we can measure directly the ionizing flux of any such source. (We know from observations of high-z quasars that the average intervening extinction and absorption is small, at least from $z = 3$ [e.g., Pei and Fall 1989].) Thus, provided the sources are not too faint (below the magnitude limit of present-day deep galaxy surveys), they should exist within number counts at these wavelengths. We can attempt therefore to determine whether a population of sources with the desired properties exists within the observed number counts and furthermore try to discover what information we can derive by combining the ionizing flux requirements with the observational data on the number and color of such sources.

For quantitative purposes, we shall assume throughout that the IGM Lyα optical depth, τ, satisfies $\tau < 0.02$ at $z = 3$ (Steidel and Sargent 1988) and $\tau < 1$ at $z = 4.5$ (derived from spectra of McCarthy *et al.* 1988). The neutral fraction at redshift z is related to τ as

$$\frac{n_{\rm H\,I}}{n_e} = 1.4 \times 10^{-4}(1+z)^{-2}(1+2q_0 z)^{1/2}h^{-1}\left(\frac{\Omega_B}{0.03}\right)^{-1}\tau(z) , \quad (1)$$

where h is the Hubble constant in units of 50 km s^{-1} Mpc^{-1} and Ω_B is the ratio of the baryon density to the closure density (Gunn and Peterson 1965). The flux J_ν required to maintain this ionization translates to

$$J(z) = 1.1 \times 10^{-29}(1+z)^{9/2}h^3\left(\frac{\Omega_B}{0.03}\right)^2\tau(z)^{-1} \text{ ergs cm}^{-2}\text{ s}^{-1}\text{ Hz}^{-1}\text{ deg}^{-2} , \quad (2)$$

where J without a subscript ν will represent $J_{\nu_{\rm L}}$, the flux at frequencies just above the Lyman-continuum edge $\nu_{\rm L}$. We have assumed $J_\nu \sim \nu^{-1}$ for $\nu > \nu_{\rm L}$, though the result depends extremely weakly on the assumed power law index because of the steep ν^{-3} dependence of the ionization cross section. We have also for simplicity set $q_0 = 0.5$ and assumed a gas temperature of $T = 10^4$ K in computing the recombination coefficient. If we denote as S_ν the average sky surface brightness of the ionizing sources at z as seen at the present time, then

$$\begin{aligned} S_\nu &= (1+z)^{-3}J(z) \\ &= 1.1 \times 10^{-29}(1+z)^{3/2}h^3\left(\frac{\Omega_B}{0.03}\right)^2\tau(z)^{-1} \\ &\qquad \text{ergs cm}^{-2}\text{ s}^{-1}\text{ Hz}^{-1}\text{ deg}^{-2} , \end{aligned} \quad (3)$$

where $\nu = \nu_{\rm L}(1+z)$. Thus $S(3600\ \text{Å}) > 4.4 \times 10^{-27}h^3(\Omega_B/0.03)^2$ and $S(5000\ \text{Å}) > 1.4 \times 10^{-28}h^3(\Omega_B/0.03)^2$ ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2} from the ionizing sources.

Another interesting constraint, an observational upper limit to $J(z)$ in the range $z = 2$–3, is given by the absence of significant Lyα emission from the damped Lyα absorption clouds seen in quasar absorption-line systems (Wolfe *et al.* 1986). Despite intensive searches by a number of groups, only one

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very marginal detection has been claimed toward Q0836+113, with a Lyα surface brightness of about 10^{-17} ergs cm^{-2} s^{-1} arcsec^{-2} (Hunstead and Pettini 1989). Smith *et al.* (1989) have found 3 σ upper limits of 10^{-17} ergs cm^{-2} s^{-1} arcsec^{-2} around four damped Lyα systems at $z = 2.3$–2.8, using filter imaging. While these searches are normally interpreted in terms of star formation rates in the cloud itself, they also limit J provided only that we assume that the damped Lyα systems are extended compared with the seeing in the measurements. Thus the surfaces of the system must absorb the incident ionizing photons in a self-shielding ionized slab which protects the neutral hydrogen core. The slabs will emit roughly one Lyα photon per ionization. Because there is a little significant dust in these systems (Pei and Fall 1989), the Lyα photons can escape relatively easily from at least the forward side of the cloud. We shall assume roughly that

$$S(\mathrm{Ly}\alpha) \sim \frac{1}{2}\, h\nu_{\mathrm{Ly}\alpha}(1+z)^{-4} \int_{\nu_{\mathrm{L}}}^{\infty} \frac{J_\nu}{h\nu}\, d\nu \qquad (4)$$

is the currently observed Lyα surface brightness arising from the ionized slabs. Therefore, if we adopt 1.3×10^{-10} ergs cm^{-2} s^{-1} deg^{-2} as an upper limit to S, then

$$J(z) < 1.6 \times 10^{-23}\left(\frac{1+z}{3.5}\right)^4 \text{ ergs cm}^{-2}\text{ s}^{-1}\text{ Hz}^{-1}\text{ deg}^{-2} \qquad (5)$$

in the range $z = 2$–3 over which the clouds have been observed. Then $S(3400) < 4.1 \times 10^{-25}$ ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2}. This constraint is independent of the Hubble constant.

Before proceeding further, we can note at once that recent spectroscopic surveys (e.g., Broadhurst, Ellis, and Shanks 1988) have found that nearly all galaxies at $B \lesssim 22$ lie at $z \ll 1$; these galaxies therefore cannot contribute significantly to the high-z ionizing flux. It follows that, unless the sources are simply too faint to have been seen, we must look for them in the magnitude range $22 < B < 27$, where $B = 27$ is the typical survey limit. Interestingly, these are the magnitudes where a significant "blue" or "flat-spectrum" population does begin to appear (Koo 1986; Tyson 1988; Cowie *et al.* 1988; Lilly, Cowie, and Gardner 1990, hereafter LCG), some of which might be candidates for the required sources at $z \sim 3$.

The LCG deep survey is ideally suited to contribute to the present discussion since it extends to a much shorter wavelength bandpass (3400 Å ± 150 Å, or U') than any other deep survey and covers the wavelengths of primary interest from 3600 to 5400 Å (U', B, and V) as well as longer wavelengths (I and K). The U' data is particularly important because it corresponds to constraints at $z = 3$ which are more stringent than those at higher redshift, and because out to this redshift we can be reasonably secure about the absence of intervening absorption or extinction, on average. Indeed, the LCG number counts at U', which are shown in Figure 1, provide an immediate insight into the problem. The average sky surface brightness at 3400 Å for sources with $22 < U'_{AB} < 26$ is approximately 3×10^{-25} ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2}. Therefore, if even $1.5 \times 10^{-2} h^3(\Omega_B/0.03)^2$ of these sources lie at $z \sim 3$, we can invoke them as the explanation of the Gunn-Peterson effect at this redshift. Between $B = 22$ and $B = 27$, the average sky surface brightness is 10^{-24} ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2} and we require only $10^{-4} h^3(\Omega_B/0.03)^2$ to lie beyond $z = 4.5$.

However, these quick estimates understate the constraints that can be derived, for two reasons. First, many of the sources included in these counts have colors that would preclude their

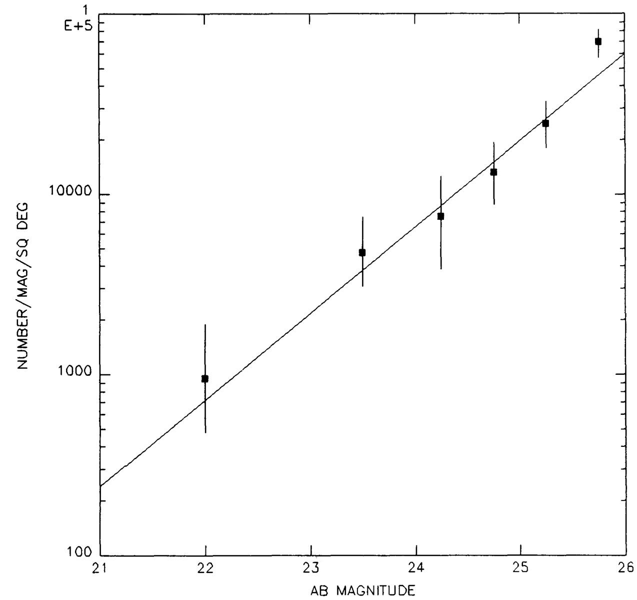

FIG. 1.—Number count (U' band) of surface density of objects per square degree and per unit magnitude in a 300 Å bandpass centered at 3400 Å. The magnitudes are given in the AB (equivalent visual) system, where $AB = -48.60 - 2.5 \log(f_\nu)$ (in cgs units) (Oke 1974).

being high-z ionizers. If we restrict ourselves to those that *can* be high-z ionizers in this magnitude range, a larger fraction will have to be at high z. Second, the expected flux from a high-z ionizer will be much larger at frequencies $\nu < \nu_{\mathrm{L}}$ than that at $\nu > \nu_{\mathrm{L}}$, and this also could impose more stringent constraints.

In order to proceed further, we must analyze the expected spectral shape of high-z ionizers, and in particular the depth of the Lyman-continuum drop, which is a sensitive function of the high-mass end of the initial mass function (IMF). We give a semianalytic discussion of this in § II. We then consider some model histories of galaxy formation and compare these with the ionization constraints and number counts in § III. Our conclusion is that we can satisfy the requirement of the ionization if at least a few percent of the total galaxy formation takes place between $z = 3$ and 5. This is discussed in § IV, where we consider whether such a population is plausibly present in the current deep samples.

II. SPECTRAL ENERGY DISTRIBUTIONS AND THE LYMAN-CONTINUUM BREAK

The problem of computing the luminosities and spectral energy distributions (SEDs) of starbursting galaxies at short wavelengths is simplified by two facts:

1. The hot massive stars that dominate the light at these wavelengths have short lifetimes ($<10^8$ yr) compared to the assumed duration of a typical burst ($\geq 10^8$ yr).

2. The massive stars that dominate the light are also those that return the metals to the ISM.

The first point allows us to compute the luminosity from the IMF and nucleosynthetic arguments directly, while the second allows us to calibrate the energy output at these wavelengths in a simple way from the mass of released metals. Thus, the luminosity per unit frequency at a given frequency ν in this range may be written as

$$L_\nu \simeq \int N(M)M[0.007 f_{\mathrm{He}}(M) + 0.001 f_Z(M)]c^2 F_\nu(M)\, dM\ , \qquad (6)$$

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where $F_\nu(M)$ is the spectral shape of stars of mass M on the main sequence, normalized such that $\int F_\nu \, d\nu = 1$. $f_{\rm He}$ is the mass fraction converted to helium, and f_Z to metals. The second term in equation (4) is of course very approximate both in the numerical constant and in the assumption of main-sequence F_ν's, but it represents only a small correction since most of the energy is released on the main sequence. Finally, $N(M)\,dM$ is the star formation rate per unit mass interval (IMF).

The rate of metal mass ejection may be written as

$$(\dot{MZ}) = \int N(M) M \phi_Z(M) dM \; , \tag{7}$$

where $\phi_Z(M)$ is the metal mass fraction ejected from a star of mass M. For $\nu = 3 \times 10^{15}$ Hz, the major contributions to the integrands of both of equations (6) and (7) come from stars of masses above about 12 $M_\odot$ that dominate the light at these wavelengths and also eject metals.

The quantity of interest in the present context is $\epsilon_\nu \equiv L_\nu/(\dot{MZ})$, the light per unit frequency per unit metal mass return. Combining equations (4) and (5),

$$\epsilon_\nu = \frac{\langle (0.007 f_{\rm He} + 0.001 f_Z) F_\nu \rangle c^2}{\langle \phi_Z F \nu \rangle} \; , \tag{8}$$

where angle brackets denote a mass-weighted average over the IMF.

We have computed ϵ_ν in the interval 400–2000 Å for a wide range of IMF power laws $[N(M) \sim M^{-\alpha}]$ and an upper mass cutoff of 60 $M_\odot$ using F_ν obtained from Kurucz (1979) and mass fractions from Woosley and Weaver (1986). The ϵ_ν shape as a function of wavelength gives the SED of the galaxy and is shown in Figure 2 for $\alpha = 2.0$, 2.35, and 2.7. In Figure 3 we show the average ϵ_ν from 1000 to 2000 Å as a function of α and also the depth of the Lyman-continuum break, defined here as $\epsilon_\nu(1000\ \text{Å})/\epsilon_\nu(800\ \text{Å})$. As expected, ϵ_ν is insensitive to the choice of IMF because the stars which produce the light are also those which eject the metals. At 1000 Å, $\epsilon_\nu = 3800$ ergs g^{-1} Hz^{-1} for $\alpha = 2$ and $\epsilon_\nu = 5500$ ergs g^{-1} Hz^{-1} for $\alpha = 3$. For a Salpeter IMF ($\alpha = 2.35$), ϵ_ν is relatively constant from 1000 to 2000 Å with a value $\epsilon_\nu = 5000$ ergs g^{-1} Hz^{-1}. We shall adopt this value in the subsequent discussion, while noting that there is a plausible uncertainty of perhaps as much as 50% owing to the choice of IMF. We also note that this adopted value is about 70% higher than the rough estimate given in Cowie (1988). For values of α between 2.0 and 2.7, it can be seen from Figure 2 that the SED is quite flat at wavelengths above about 1100 Å, as was found by Meier (1976) for Salpeter models. The Lyman-continuum break ranges from a value of 3.75 at $\alpha = 2$ to about 6 at $\alpha = 2.7$.

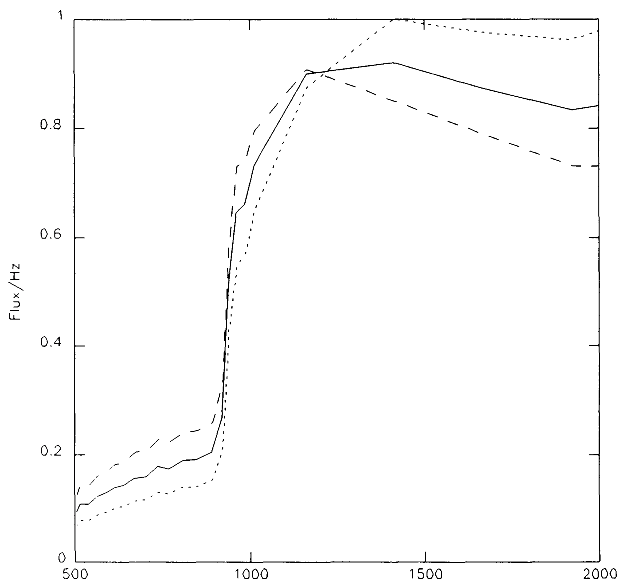

FIG. 2.—ϵ_ν shapes from 500 to 2000 Å for an assumed IMF of $N(M) \sim m^{-\alpha}$ to an upper mass cutoff of 60 $M_\odot$ and $\alpha = 2.0$ (*dashed*), $\alpha = 2.35$ (*solid*), and $\alpha = 2.7$ (*dotted*).

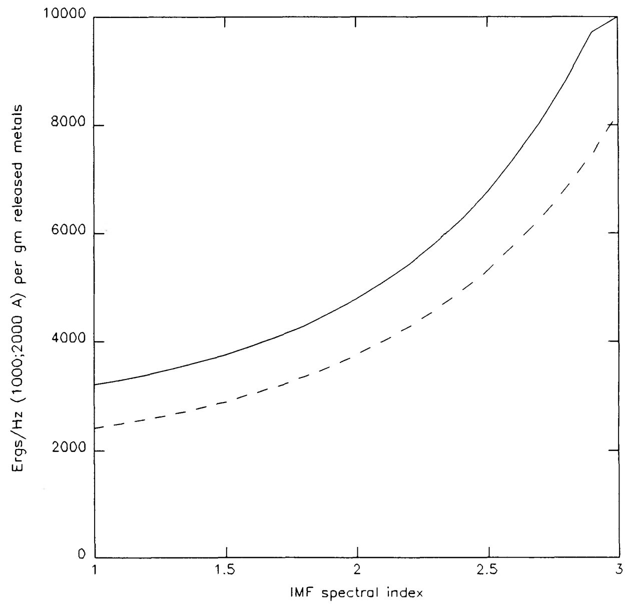

FIG. 3.—The average value of ϵ_ν between 1000 and 2000 Å (*solid line*) and of the Lyman break (*dashed*), shown as $\epsilon_\nu(1000\ \text{Å})/\epsilon_\nu(800\ \text{Å}) \times 1000$, as a function of α. The break ranges in value from 2 to just under 8 as α varies from 1 to 3.

As is well known, the presence of any small amount of neutral hydrogen in the objects would enormously increase the depth of the Lyman-continuum break (Meier 1976). Thus the galaxies must be predominantly ionized and transparent to the ionizing radiation if they are to act as ionization sources for the IGM. They must also be relatively dust-free if they are not to be significantly attenuated by UV extinction. Neither constraint is implausible in a young galaxy where intense star formation has just initiated and where significant metals have not yet formed. However, the only direct evidence on this question is the SED observed for the rapidly star-forming galaxy SSA 22–24 (Cowie and Lilly 1989), which may lie at a redshift of $z \sim 3$. The SED for this object is compared with an $\alpha = 2$ model in Figure 4 and matches extremely well, with a Lyman-continuum break of 3.7. The line tentatively identified by Cowie and Lilly (1989) as possible Lyα is weak (26 Å equivalent width), and only marginally significant, and there are no other lines present at this level, which is consistent with little of the ionizing radiation being absorbed in the galaxy. A fully opaque galaxy would give Lyα equivalent widths of several hundred angstroms (Meier 1976). As we shall discuss subsequently, any significant attenuation of the ionizing flux emergent from the galaxy would cause serious problems in explaining the ionizing background. In particular, systems such as the damped Lyα

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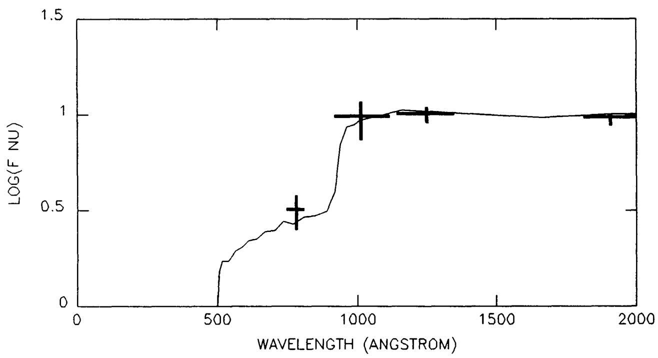

FIG. 4.—A comparison of the computed shape for an $\alpha = 2$ model with the observed SED of SSA 22–24, which Cowie and Lilly (1989) have suggested is a galaxy which is rapidly forming stars at a redshift of ~ 3.

clouds, which contain high column densities of neutral hydrogen, cannot contain the bulk of star formation. This is consistent with the failure to detect Lyα in these systems (e.g., Smith *et al.* 1989).

A simple model which provides a reasonable representation of all the data is to set

$$\begin{aligned} \epsilon_\nu &= 5000\nu^0 \text{ ergs g}^{-1}\text{ Hz}^{-1}, && \nu < \nu_L \\ &= 1400\phi\left(\frac{\nu}{\nu_L}\right)^{-1} \text{ ergs g}^{-1}\text{ Hz}^{-1}, && \nu_{He} > \nu > \nu_L \end{aligned} \tag{9}$$

where $\phi = 1$ for an optically thin galaxy with an $\alpha = 2$ IMF, and $\phi < 1$ (and may be obtained from Fig. 3) for steeper IMFs or if there is a significant neutral hydrogen opacity.

As we discussed in the introduction, many sources in the magnitude range $22 < B < 27$ cannot be $z \sim 3$ ionizers because of their observed colors. We can now quantify this with the computed SEDs. Let us consider a source that is a significant ionizer at $z = 3$. Since the flux drops rapidly when the He I edge (ν_{He}) at 504 Å redshifts through ν_L, such a source must have a redshift between 3 and 5.4. This means that the source should have a flat-spectrum region (Fig. 2) which should run, at the present epoch, from roughly the V band through to the I band, and, at the lower end of the redshift range, from B through to I. However, the galaxies should have a substantial break (more than a magnitude) at a wavelength between the U' and the V bands, corresponding to the Lyman-continuum break which must be beyond 3650 Å. As was found by Tyson (1988) in his deep samples, the LCG sample also shows that a large fraction of galaxies are flat to within 0.5 mag in $B - I$ or $V - I$ as a function of I magnitude for $23 < I < 25$. We refer to the galaxies that are flat in $B - I$ as the "flat-spectrum" population and galaxies which satisfy this criterion as "flat" though, strictly speaking, most are slightly redder than flat. Galaxies that also have flat $U' - I$ must lie at $z < 2.7$ and can be excluded as $z \gtrsim 3$ ionizers, but some of the flat $B - I$ sources are not flat in $U' - I$. Now the average sky surface brightness of this candidate population at I is 4.3×10^{-25} ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2}. The ionizing flux is then 1.2×10^{-25} ϕ ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2} from the assumed SED shape (eq. [9]). Comparing this with the required flux of $4.4 \times 10^{-27} h^3(\Omega_B/0.03)^2$ ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2}, we can see that at least $4\phi^{-1}h^3(\Omega_B/0.03)^2$% of the flat-spectrum sources would have to lie at $z \sim 3$. For $1 < h < 2$ and $\phi > 0.3$, we require 4%–100% of the flat sources to lie at this redshift.

We can draw a number of conclusions from this discussion. First, it is clear that there does exist a population that could plausibly be the source of the ionization at $z \sim 3$ and that this population can adequately provide the ionizing flux. A corollary is that, if the flat-spectrum galaxies are the source of the ionizing flux, a minimum of $4h^3\phi^{-1}$% of them must lie at $z \sim 3$. It is clear that if $H_0 = 100$ km s^{-1} Mpc^{-1} ($h = 2$) or if $\phi < 1$ (i.e., the Lyman break is greater than the assumed minimum value of 3.7) then a substantial fraction of these objects would have to be at this redshift. Finally, if there is substantial intrinsic neutral hydrogen opacity ($\phi \ll 1$) the models will fail.

III. EVOLUTION OF THE IONIZING FLUX

An alternative approach to the problem is to model the evolution of the ionizing flux theoretically (Bechtold *et al.* 1987). Section II provides the tools to carry out this calculation in a highly model-independent fashion by normalizing to metal production, and we shall do so in this section.

First, we recall that the currently observed surface brightness of a population of objects at a redshift z which produces a present volume density of metals (ρZ) is given by (Lilly and Cowie 1987; Cowie 1988)

$$S_\nu = \frac{1}{4\pi} \epsilon_{\nu 0}(\rho Z)c \, , \tag{10}$$

where $\nu = \nu_0/(1 + z)$. If the redshifted frequency corresponds to frequencies where the source spectrum is flat, then $\epsilon_{\nu 0}$ is constant and S_ν is independent of redshift. More generally, therefore, we obtain that the surface brightness produced by all sources lying at a redshift such that the observed wavelength lies in the flat-spectrum region of the source is given by equation (3) *independently of the redshift distribution* (Lilly and Cowie 1987; Cowie 1988). Numerically, with $\epsilon_\nu = 5000$ ergs g^{-1} Hz^{-1},

$$S_\nu = 3.6 \times 10^{-25}\left(\frac{\rho Z}{10^{-34} \text{ g cm}^{-3}}\right) \text{ ergs cm}^{-2}\text{ s}^{-1}\text{ Hz}^{-1}\text{ deg}^{-2} \, . \tag{11}$$

The utility of equation (11) lies in estimating the cosmological importance of an observed flat-spectrum population. Given such a population, we know the observed wavelengths where the sources are flat and should satisfy equation (11). We can then use the measured contribution to the EBL to determine the quantity of metals released by the population.

We can generalize this type of analysis to estimate the ionizing flux from the forming galaxies if we know the current metal density that they have produced. Quantitatively, if we ignore opacity effects for the moment, the population of flat-spectrum galaxies contributes an intensity $J_{\nu 0}(z_0)$ at frequency ν_0 and redshift z_0 given by

$$J_{\nu 0}(z_0) = \frac{c}{4\pi}(\rho Z)(1 + z_0)^3 \int_\infty^{z_0} g(z)\epsilon_\nu \, dz \, , \tag{12}$$

where ϵ_ν is the emission per unit frequency per unit mass of produced metals of the galaxy as in the previous section, $g(z)$ is the fraction of galaxies formed per unit redshift [$\int g(z)dz = 1$], and $\nu_0 = \nu(1 + z)/(1 + z_0)$. Then if we know the current density of metals we can test whether a particular $g(z)$ distribution satisfies the ionization constraints and does not violate the limits on the flat-spectrum populations from number counts.

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The neglect of the opacity of a continuously distributed IGM in the above discussion is simply justified by the lack of significant recombination in this medium. The ratio of ionizing photons produced to baryons is given by

$$\frac{n_{\rm ion}}{n_{\rm baryon}} \approx 200\left(\frac{\rho Z}{10^{-34}\ {\rm g\ cm^{-3}}}\right)\phi G(z)\left(\frac{\Omega_B}{0.03}\right)^{-1} h^{-2}\ , \quad (13)$$

where $G(z) = \int_{\infty}^{z} g(z)dz$ is the cumulative distribution of the galaxy formation. There can be no significant opacity, therefore, when more than a few percent of galaxy formation has taken place. This does not address the question of the shadowing by dense neutral or dusty clumps in the IGM. This is an open question at the higher redshifts, and we only note that if this is a very significant effect, just as if the galaxies themselves are opaque, the models will fail.

The most uncertain quantity in such an analysis (though not at a level that causes a serious problem) is the current density of metals in various populations with which to compare results derived from equation (5). In Cowie (1988) we estimated that current spheroids contain $1.4 \times 10^{-34}h^2$ g cm^{-3} and current disks $2.2 \times 10^{-34}h^2$ g cm^{-3} of metals, but such estimates are full of uncertainties in assumed light densities, baryonic mass-to-light ratios and metallicities. Additionally, much of the metal formation, in the disks at least, is associated with star formation at $z \ll 3$. A further problem is that we do not know how effective galaxies were in retaining produced metals.

Some of these difficulties can be avoided by using instead the metal mass-to-light ratio obtained from clusters of galaxies, where most of the baryons and metals lie in the cluster atmosphere rather than the stars. In particular, a deeper cluster atmosphere is presumably much more effective at retaining metals than the galaxies. For example, Coma has a gas mass of $1.6 \times 10^{14}h^{-5/2}\ M_\odot$ within $2h^{-1}$ Mpc (Cowie, Henrikson, and Mushotzky 1987) and $L_V = 8.7 \times 10^{12}h^{-2}\ L_\odot$ within this radius. The average metallicity of the gas is around 0.01, based on the most accurate X-ray data on iron (Mushotzky 1984) though less accurate optical studies of cooling-flow systems can give values comparable to or slightly higher than cosmic for elements such as oxygen (e.g., Hu, Cowie, and Wang 1985). Adopting the X-ray value, we have $(MZ/L_V) = 0.19h^{-1/2}$ or $(MZ/L_B) = 0.24h^{-1/2}$. Now, combining this metal mass-to-light ratio obtained from the clusters with the total blue light density of $9 \times 10^7h\ L_\odot$ Mpc^{-3} of all galaxies, given by Kirshner, Oemler, and Schechter (1979), and with King and Ellis's (1985) estimate of 40% associated with bulges and spheroids, gives a blue luminosity density of $3.6 \times 10^7h\ L_\odot$ Mpc^{-3} for the spheroids, and in turn a $(\rho Z) = 5.9 \times 10^{-34}h^{1/2}$.

Even this cluster metallicity argument is quite uncertain because it assumes that the metallicity is constant throughout the gaseous atmosphere and equal to the core value, and because it neglects the effects which gas loss to the atmosphere may cause in the member galaxies. These effects may suggest that the value of (ρZ) determined from clusters is a high-end estimate. For the present analysis, we shall therefore adopt a value of $10^{-34}h^2$ g cm^{-3} for the current metal density associated with high-z galaxy formation, keeping in mind that the value could be several times higher. Equation (12) now becomes

$$J_{\nu 0}(z_0) = 1.0 \times 10^{-25}(1+z_0)^3h^2 \int_{\infty}^{z_0} g(z) \times \left(\frac{\epsilon_\nu}{1400\ {\rm ergs\ g^{-1}\ Hz^{-1}}}\right)dz \quad (14)$$

in ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2}. With the simple functional form of equation (9), this reduces to

$$J(z_0) = 10^{-25}(1+z_0)^4h^2 \int_{z_0}^{z_0\nu_{\rm He}/\nu_{\rm L}} g(z)(1+z)^{-1}\,dz\ . \quad (15)$$

We can now consider various models for $g(z)$ and determine whether they are consistent with the ionization requirements. Some simple functional forms are easily integrable and we consider these first. If $g(z)$ is constant from $z = 0$ to $z = z_{\rm max}$, then $g(z) = (1 + z_{\rm max})^{-1}$ and

$$J(z_0) = 10^{-25}h^2 \frac{(1+z_0)^4}{(1+z_{\rm max})} \ln\left[\frac{(1+z_0\,\nu_{\rm He}/\nu_{\rm L})}{(1+z_0)}\right] \ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}\ deg^{-2}} \quad (16)$$

for $z_0 < z_{\rm max}\,\nu_{\rm L}/\nu_{\rm He}$. Now if, for example, we take $z_{\rm max} = 10$ we find for $z_0 = 3$ that $J(z_0) = 10^{-24}h^2$ ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2} compared with a required value of $3 \times 10^{-25}h^3(\Omega_B/0.03)^2$ ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2} from equation (2). Thus a small percentage of the galaxy formation occurring in the range $z = 3$–5 will satisfactorily meet the requirements.

If $g(z)$ peaks strongly at a redshift z_R, then we can also integrate equation (15) since we can represent $g(z)$ as $\delta(z - z_R)$. Then

$$J(z_0) = 10^{-25}h^2 \frac{(1+z_0)^4}{(1+z_R)} \ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}\ deg^{-2}} \quad (17)$$

for $z_R\,\nu_{\rm L}/\nu_{\rm He} < z_0 < z_R$. In this case, the fluxes easily satisfy the ionization constraint at $z_0 = 3$, provided z_R is not greater than 5.4, but fail if the galaxy formation is at higher redshift.

Finally, we consider an empirical distribution. We set $g(z) = 0.05$ for $z < 2.7$, $g(z) = 0.75$ between 2.7 and 3.7, $g(z) = 0.20$ in the range 3.7–5.0 and $g(z) = 0$ beyond $z = 5.0$. Figure 5 shows that the ionizing flux obtained with this $g(z)$ model easily satisfies all the ionization constraints including the upper limit set by the damped Lyα clouds.

IV. DISCUSSION

We conclude that the ionization of the IGM at redshifts between 3 and 4.5 can be understood if at least $4h^3\phi^{-1}$% of galaxy formation occurred between redshifts, and moreover

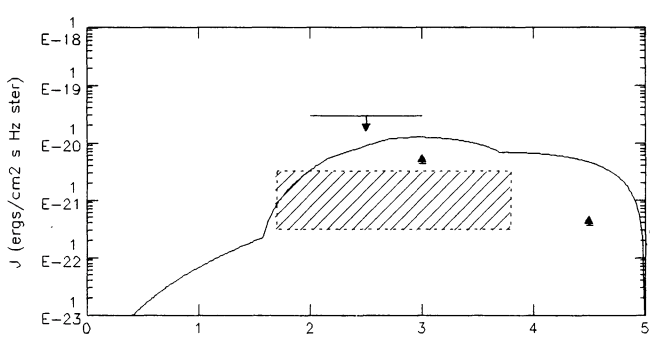

FIG. 5.—The flux $J(z)$ just below the Lyman-continuum edge as a function of z for an empirical model based on observed counts and colors. The arrows show the various ionization limits discussed in § I, while the hatched region is the area where Bajtlik, Duncan, and Ostriker (1988) suggested J_ν should lie, based on an analysis of the Lyα clouds. All limits are shown for $H_0 = 100$ km s^{-1} Mpc^{-1} ($h = 2$) which provides the tightest constraints. (For comparison with other published work, the flux is expressed as sr^{-1}. To compare with flux quoted as deg^{-2} in the text, multiply by 3.04×10^{-4}.)

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that objects exist within the observed populations which could be at the required redshifts and easily provide sufficient ionizing flux. On both observational and theoretical grounds, therefore, it is possible to explain the ionization at redshifts between 3 and 4.5 by rapidly star-forming galaxies.

If this interpretation is correct, a considerable fraction of the flat-spectrum galaxies may lie at redshifts ~ 3. Galaxies at higher redshift will be significantly modified by the Lyα forest and Ly limit systems in the IGM and may not be easily recognized, but this does not apply at $z = 3$, where a galaxy that is rapidly forming stars would appear as a flat-spectrum object. In this final section, we shall discuss the evidence that some of the flat-spectrum population could lie in the required range of redshifts and be the source of the ionizing flux.

As Tyson (1988) first pointed out, the flat-spectrum galaxies onset abruptly at a B magnitude of around 23. This population appears very rapidly indeed, as can be seen from Figure 6, which uses data both from the LCG survey and a much wider field sample from Hu and Cowie (1990), and which shows the fraction of objects with $(B - I) < 2.0$ as a function of I magnitude. The new population onsets and reaches a fairly constant fraction (nearly 50%) in less than a magnitude. This implies in turn that the population must onset over a range Δz such that $\Delta z/z \ll 1$. From this we can reasonably infer that the population does not lie anywhere near to us (i.e., $z \lesssim 0.1$) since otherwise we would require to turn on this population simultaneously without an obvious clock to set the timing.

The abrupt onset of the population can also be seen in the average color of the objects on the sky, which changes suddenly to a much flatter spectral shape at $I = 22$. This is shown in Figure 7*a*. We can use this information to infer the color of the new population by assuming that half of the population in the fainter magnitude ranges is new and that the remaining half has average colors similar to those of the slightly brighter population (cf. Fig. 6). We can then decompose the relative contributions as shown in Figure 7*b* and Figure 8.

As can be seen in Figure 8, the normal population at these magnitudes has an average color similar to that of a spiral galaxy with modest redshift, but the spectral shape of the flat-spectrum population is much closer to that of an irregular galaxy with modest redshift. However, there is no plausible way to fit this component with a low-z irregular population. Such objects would have to lie at $z < 0.2$, so that the Balmer break would not have passed through the B band, in order to reproduce the flat BVI colors (cf. Fig. 8), and we are reduced to postulating that all the objects lie in a thin shell around $z \sim 0.1$, a conclusion that makes little sense. However, given

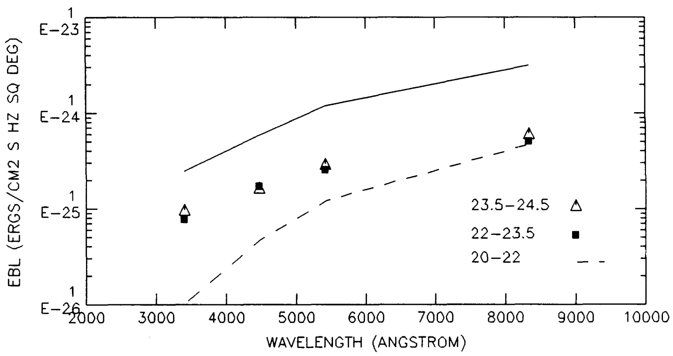

FIG. 7*a*

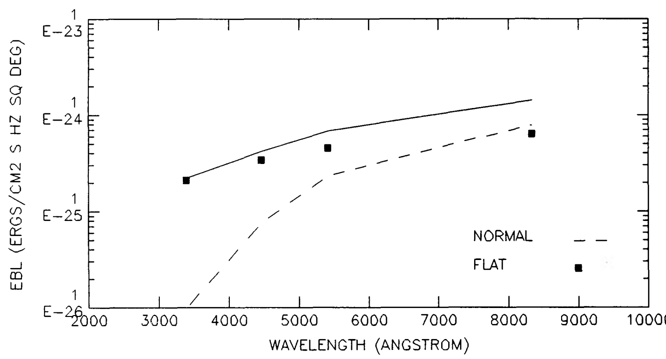

FIG. 7*b*

FIG. 7.—(*a*) The average sky brightness of galaxies with $19.5 < I < 24.5$ is shown as a solid line. Also shown are the average sky brightness per unit magnitude in the ranges $I = 20$–22 (*dashed*), 22–23.5 (*boxes*), and 23.5–24.5 (*open triangles*). As can also be seen in Fig. 6, note the abrupt change in color at $I = 22$. (*b*) The average sky brightness of galaxies with $22 < I < 24.5$ (*solid line*). Also shown is the decomposition if 55% of the galaxies in this range of I magnitude have colors similar to those at $19.5 < I < 22$ (*dashed line*). The remaining light (corresponding to the new population) is given by the solid boxes.

this, it is then clear that the Balmer break must lie beyond I. Hence $z > 1.5$. Finally, the Lyman-continuum break at 912 Å cannot have passed through the B band, which then implies that the population lies at $1.5 < z < 3.7$. Only a fraction of objects can lie beyond $z = 3.7$ because of the flat color between B and V.

It appears quite likely therefore that many of the flat-spectrum galaxies are a population lying between $z = 1.5$ and $z = 3.7$. We can now invoke equation (11) to compare their average light with that expected from galaxy formation. This is shown as a shaded region in Fig. 8, and we note that the flat-spectrum population corresponds to a major fraction of the galaxy formation. Finally, we note that the U' band flux falls within the ionization constraints, as we knew already from the work of the previous two sections.

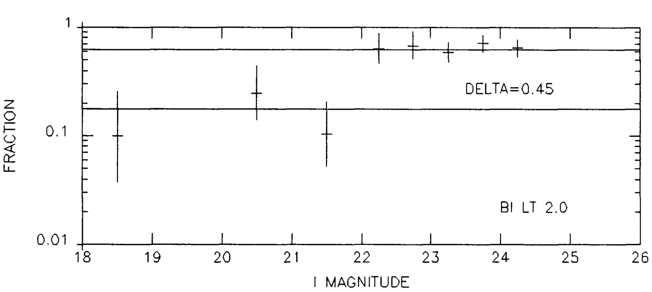

FIG. 6.—The fraction of objects with $(B - I) < 2.0$ as a function of I magnitude (measured in a 3″ aperture). The fraction changes abruptly from just under 20% at $I < 22$ to just over 60% at $I > 22$. Delta is the difference between the fractions at faint and bright magnitudes.

V. CONCLUSIONS

We have argued that the high-z ionization required to explain the absence of detectable Lyα continuum absorption can plausibly be attributed, both observationally and theoretically, to starbursting galaxies at $z = 3$–5. We have also argued that some of the flat-spectrum galaxies seen at $I > 22$ could correspond to part of such a population at $z \sim 3$, based on the properties of their average colors between 3400 Å and 22,000 Å. It is clear from the discussion that, if many of the flat-

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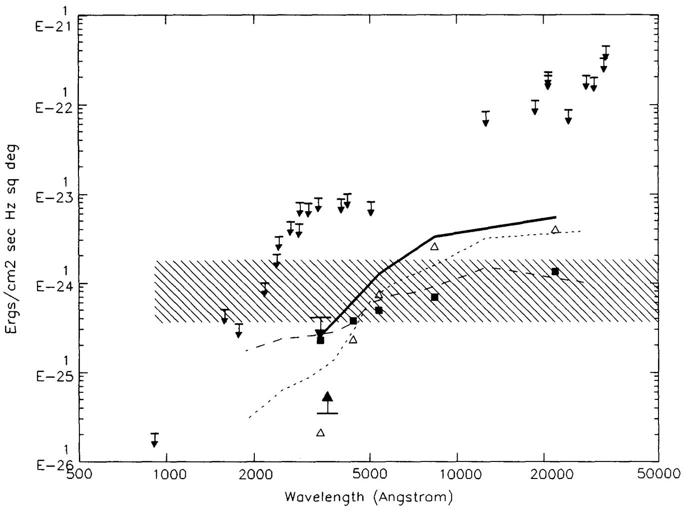

FIG. 8.—The average sky brightness of the normal population (*open triangles*), the flat spectrum population (*solid boxes*), and the total light (*thick solid line*) between U' and K for $19.5 < I < 24.5$. Also shown for comparison are the shapes of an Sbc (*dotted*) and Im (dashed) galaxy at $z = 0.25$ (from Coleman, Wu, and Weedman 1980). The cross-hatched region shows the sky surface brightness expected from the flat spectrum region of a population of forming galaxies, as derived from eq. (11), while the arrows with short baselines show measured upper limits on the extragalactic background light as summarized in Cowie (1988), together with a limit at a wavelength just less than 912 Å given in Songaila, Bryant, and Cowie (1989). Finally, the broad arrows summarize the ionization constraints for $H_0 = 100$ km s^{-1} Mpc^{-1} or $h = 2$. The lower arrow scales as h^3; the upper, as h^0.

spectrum sources do lie at $z \sim 3$, then the IGM will be so highly ionized that the Lyα continuum opacity will be extremely hard to detect. Referring to Figure 5, we can see that, even for $H_0 = 100$ km s^{-1} Mpc^{-1} (the easiest case) we would require a substantial improvement in sensitivity to have a detectable τ at both $z = 3$ and $z = 4.5$. By contrast, it is clear that only a small increase in sensitivity is required to detect the surfaces of the damped Lyα clouds. Again from Figure 5 we can see that a factor of 2 increase in sensitivity might result in a positive detection.

Finally, it is interesting to speculate that the same sources that are responsible for high-z ionization might also produce the as yet unidentified portion of the diffuse X-ray background up to 100 keV. In support of this idea, it is clear that the flat-spectrum sources are one of the few known populations which have a sufficiently high surface density to be consistent with fluctuation analyses on the X-ray background which require more than 5000 objects per square degree (e.g., Hamilton and Helfand 1987). If they are the sources, they must emit about 5% of their optical luminosities in the X-ray to produce the bolometric X-ray surface brightness of around 3×10^{-11} ergs cm^{-2} s^{-1} deg^{-2} (Boldt and Leiter 1987). This is too high for most mechanisms such as hot winds or X-ray binary activity (Bookbinder *et al.* 1980), and the most likely possibility would be AGN in the sources radiating primarily in the X-ray band (Boldt and Leiter 1987). Individual sources should have bolometric X-ray luminosities of around 5×10^{-15} ergs cm^{-2} s^{-1}, close to the AXAF detection limit.

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