LYMAN-CONTINUUM EMISSION FROM GALAXIES AT $z \approx 3.4$  

**Charles C. Steidel**
Palomar Observatory, California Institute of Technology, MS 105–24, Pasadena, CA 91125

**Max Pettini**
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

**AND**

**Kurt L. Adelberger**
Palomar Observatory, California Institute of Technology, MS 105-24, Pasadena, CA 91125

Received 2000 August 17; accepted 2000 August 24

**ABSTRACT**

We report the detection of significant Lyman-continuum flux in the composite spectrum of 29 Lyman-break galaxies (LBGs) with redshifts $\langle z \rangle = 3.40 \pm 0.09$. After correction for opacity due to intervening absorption using a new composite QSO spectrum evaluated at the same redshift, the ratio of emergent flux density at 1500 Å in the rest frame to that in the Lyman continuum is $L(\lambda 1500)/L(\lambda 900) = 4.6 \pm 1.0$. If the relative intensity of the inferred escaping Lyman-continuum radiation is typical of LBGs at $z \sim 3$ (the galaxies in this sample are drawn from the bluest quartile of LBG spectral energy distributions due to known selection effects), then observed LBGs produce about 5 times more H-ionizing photons per unit comoving volume than QSOs at $z \sim 3$. The associated contribution to the metagalactic ionizing radiation field is $J_{l}(\lambda 912) \approx 1.2 \pm 0.3 \times 10^{-21}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$ at $z \sim 3$, very close to most estimates of the radiation field background based on the “proximity effect.” A preliminary analysis of the density of faint QSOs in our Lyman-break galaxy survey indicates that the standard extrapolated QSO luminosity function may slightly overpredict the QSO contribution to $J_{l}(\lambda 912)$ at $z \sim 3$. We briefly discuss the implications of a galaxy-dominated UV background at high redshifts.

**Subject headings:** galaxies: distances and redshifts — galaxies: formation — intergalactic medium — large-scale structure of universe

1. **INTRODUCTION**

The question of the origin of the UV radiation field that reionized the universe at $z > 6$ and maintained the ionization of the intergalactic medium at lower redshifts has been addressed numerous times since it was first considered 20 years ago (Sargent et al. 1980). The relative contributions of QSOs and massive stars in galaxies to the ionizing photon budget at high redshifts has important implications for the spectral energy distribution of the ionizing background (Miralda-Escude & Ostriker 1990; Steidel & Sargent 1989), which in turn affects the equation of state of the diffuse intergalactic medium. Early consideration of the evolution of the diffuse intergalactic medium suggested that the observed QSOs would have an increasingly difficult time producing enough ionizing photons to explain the absence of an observed Gunn-Peterson (1965) effect at redshifts $z \sim 3$ (e.g., Donahue & Shull 1987; Shapiro & Giroux 1987), suggesting the need for additional sources of ionizing photons at high redshift.

The contribution of star-forming galaxies to the UV background was first explicitly considered by Bechtold et al. (1987), but at the time there was little relevant data. Progress in very deep galaxy surveys (e.g., Sougaila, Cowie, & Lilly 1990; Steidel & Hamilton 1993) suggested that high-redshift ($z \gtrsim 3$) star-forming galaxies might well exist, but many uncertainties regarding their contribution to the ionizing background remained, due to the lack of spectroscopic redshift identifications and the uncertain opacity of galaxies to their own Lyman-continuum radiation.

The advent of the Keck telescopes in the mid-1990s made possible spectroscopy of large numbers of star-forming galaxies at redshifts $z \sim 3$, where the strongest constraints on the properties of the intergalactic medium were available from QSO absorption-line surveys, where the ability of known QSOs to maintain the ionization of the IGM became uncertain, and where the rest-frame Lyman limit of hydrogen could be observed from the ground. This population of UV-bright star-forming galaxies (Steidel et al. 1996), generally referred to as Lyman-break galaxies (LBGs), is selected photometrically by exploiting the continuum discontinuity near the rest-frame Lyman limit due to the intrinsic spectral energy distribution of hot stars, Lyman-continuum opacity from H $\alpha$ layers in the galaxy itself, and, most model-independently, the opacity of the intergalactic medium due to intervening H $\alpha$ (e.g., Madau 1995). While this large continuum break (only a portion of which is expected to be intrinsic to the galaxy) makes the discovery of LBGs extremely straightforward and statistically complete, it also makes the measurement of leaking Lyman-continuum radiation exceedingly difficult, even with 10 m class telescopes.

The problem of intergalactic H $\alpha$ opacity can be minimized by observing the Lyman continuum in galaxies at smaller redshifts, but this requires observations in the vacuum UV from space. The most sensitive direct measurement to date, by Leitherer et al. (1995), used Hopkins Ultraviolet Telescope far-UV spectra of four nearby starburst galaxies to place constraints on the fraction of Lyman-continuum photons escaping the galaxies, $f_{\text{esc}} < 3\%$ (but see Hurwitz, Jelinsky, & Dixon 1997). Similarly small upper

---

1. Based on data obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA, and was made possible by the generous financial support of the W. M. Keck Foundation.
2. Packard Fellow.
limits for relatively nearby galaxies have been set by several groups using less direct methods. Nevertheless, it is not clear how relevant these limits are to the situation at high redshift, where galaxies that simultaneously possess very large UV luminosities and low UV extinction are much more common (cf. Adelberger & Steidel 2000).

This paper presents what we believe to be the first direct detection of Lyman-continuum flux from galaxies, made possible by a high-S/N composite spectrum formed from a relatively small subset of \( z > 3 \) LBGs that are at high enough redshift to bring the rest-frame Lyman limit into a region of good spectroscopic sensitivity for current instrumentation. This measurement, which we currently regard as plausible but tentative, has significant implications for the nature of the UV radiation field at high redshifts. In the context of evaluating the significance, we also present some preliminary results on the contribution of faint QSOs to the \( z \sim 3 \) UV background.

2. DATA

The spectra selected for this study were chosen from among the 875 spectra of \( z > 3 \) LBGs we have obtained with the Keck telescopes and Low Resolution Imaging Spectrometer (Oke et al. 1995) between 1995 October and 1999 November. All of the spectra were obtained using the same instrumental configuration, a 300 lines mm\(^{-1}\) grating blazed at 5000 Å and a slit mask with 1.4 slits, providing a spectral resolution of \( \sim 12.5 \) Å in the observed frame. The typical total exposure time was 7200 s. In its current configuration, the total throughput of LRIS with this grating is \( \sim 20\% \) at 4000 Å and \( \sim 10\% \) at 3800 Å; in order to include only spectra with adequate sensitivity at the rest-frame Lyman limit, we have confined ourselves to the small subset of our spectra that have \( z \geq 3.300 \) and \( \alpha \leq 25.0 \) (81 objects). Some of these spectra did not reach the Lyman limit on the blue side, due to the geometry of the slit masks, and some were obtained under poor conditions, were contaminated by light from neighboring galaxies, or were affected by other obvious problems. Two-dimensional sky-subtracted spectrograms of each object were inspected for any sky-subtraction problems, and only the cleanest looking slits with no obvious contamination by light from neighboring galaxies, or were affected by other obvious problems. Two-dimensional sky-subtracted spectrograms of each object were inspected for any sky-subtraction problems, and only the cleanest looking slits with no obvious sky-subtraction problems were retained. The final sample consists of 29 spectra with \( \langle z \rangle = 3.40 \pm 0.09 \); the average properties of the LBGs are summarized in Table 1. The important observed-frame spectral region for evaluating the Lyman continuum is \( 3880-4020 \) Å at the average redshift.

The composite spectrum of the LBGs was constructed by shifting each extracted, one-dimensional, flux-calibrated spectrum into the rest frame and averaging after scaling to a common median in the rest-wavelength range 1250–1500 Å. A simple rejection scheme was used, in which equal numbers of positive and negative outliers were excluded from the average at each dispersion point (primarily in order to exclude sky-subtraction residuals near bright night-sky lines). The overall nature of the coadded spectrum was found to be insensitive to the number of points excluded from the average at each dispersion point. The final spectrum, shown in Figure 1, results from the rejection of two positive and two negative outliers from each dispersion point. The composite spectrum does not depend strongly on the adopted scheme for combining the individual spectra.

The composite spectrum clearly shows the net effects of the Ly\(\alpha \) forest shortward of the Ly\(\alpha \) emission line, reducing the flux by a factor of \( \sim 1.8 \) relative to the flux in the 1250–1500 Å range. Also evident is the general diminution of the flux shortward of Ly\(\beta \) due to increasing numbers of intervening and intrinsic absorption features. Many stellar and interstellar absorption features can be recognized in the composite spectrum; the most prominent are labeled in Figure 1. Interestingly, averaging the Ly\(\alpha \) forest absorption over many sight lines brings out stellar and interstellar lines that are normally masked by the forest in any single spectrum. Stellar C\(\text{III}\) at 1176 and H\(\alpha \) at 1084 Å (cf. Walborn & Bohlín 1996; Fullerton et al. 2000), and interstellar Ly\(\beta \), Ly\(\gamma \), and Ly\(\delta \) are the clearest examples. The Ly\(\alpha \) equivalent width in the composite spectrum in Figure 1 is 19.7 Å , placing it in the top 20%–25% of LBGs in terms of Ly\(\alpha \) line strength (cf. Steidel et al. 2000). This large Ly\(\alpha \) equivalent width results from a selection bias in our Lyman-break sample toward bluer objects at higher redshifts; at \( z \sim 3.4 \), galaxies will satisfy our color-selection criteria only if their intrinsic broadband colors lie in the bluest quartile of observed LBG UV colors, and a strong contribution from Ly\(\alpha \) emission helps galaxies achieve the required blue broadband color. See Steidel et al. (1999) for a more complete discussion. The impact of this selection effect on our present results is considered in § 4 below.

The bottom panel of Figure 1 shows residual flux in the Lyman-continuum region. We have chosen to evaluate the residual flux over the rest-wavelength range 880–910 Å, for two main reasons: first, the incidence of intervening Lyman-limit absorption systems (Sargent, Steidel, & Boksenberg 1989; Stengler-Larrea et al. 1995) at \( z \sim 3.4 \) means that broadband evaluation of the decrement across the Lyman limit is not likely to provide a good estimate of the emergent spectrum from the galaxies—the mean free path of a Lyman-continuum photon at \( z \sim 3 \) is only \( \Delta z \simeq 0.17 \) (Haardt & Madau 1996), corresponding to \( \sim 35 \) Å in the rest frame at \( z \sim 3.4 \). Second, the 880–910 Å range includes observed spectral regions that are still within the range for which LRIS provides adequate throughput for the entire range of redshifts included in the composite spectrum. While the significance per resolution element of the residual
fig. 1.—Composite spectrum of Lyman-break galaxies at \( z = 3.40 \) (red histogram), together with a composite QSO spectrum drawn from QSOs over the same range of redshifts (blue histogram), as described in the text. The spectrum has been boxcar-smoothed by 1 resolution element. The position of the rest-frame Lyman limit is indicated by a vertical dotted line. Note the average residual flux in the Lyman continuum, evaluated from 880-910 Å in the rest frame, indicated by the dark horizontal line segment in the bottom panel. Positions of some notable interstellar and stellar absorption features are indicated. Stellar features with no possible interstellar contributions are indicated by an “s”.

flux in the Lyman continuum is low, the net flux observed over the rest-frame 30 Å bandpass is formally significant at the 4.8 \( \sigma \) level (see Table 2).

An obvious concern in gauging the reality of the residual flux, which corresponds to an average observed flux density of \( m_{AB} = 27.4 \) in the narrow wavelength range, is the extent to which systematic problems with sky subtraction might mimic residual Lyman-continuum flux. We experimented extensively with the data, using a number of different tests. First, we confirmed that the signal is not contributed by a few outlier spectra by combining the one-dimensional spectra using different subsets with different outlier-rejection algorithms. We checked for overall systematics in the two-dimensional sky subtraction by combining the two-
dimensional background-subtracted slitlets after rebinning in the wavelength direction to a common rest-wavelength interval, registering on the spatial position of the LBG, and then experimenting with various methods of residual background subtraction (i.e., second-pass subtraction of the background that might eliminate systematics that were too subtle to notice in any single slitlet). We then evaluated the residual flux in the appropriate wavelength range both on and off the spatial positions of the detected continuum longward of the Lyman limit; the results are consistent with the residual flux measured from the stacked one-dimensional spectra, although all the additional image processing necessary to combine the spectra in two dimensions could itself be a source of systematic errors. Probably the most direct test of sky-subtraction systematics is to examine spectra, taken with the same instrumental configuration (all observed on slit masks as part of the general LBG survey) of similar objects that are known to have optically thick Lyman limits at the same observed wavelengths as the region of interest for the LBGs. In our spectroscopic LBG survey, we have observed three faint (\(z = 22.0, 22.2,\) and 23.6) QSOs that have optically thick Lyman limit systems (confirmed subsequently with long-slit observations at higher dispersion) in the redshift range \(3.29 \leq z_{\text{LLS}} \leq 3.43.\) These spectra were shifted into the rest frame of the intervening Lyman-limit system, scaled, and averaged to produce the composite spectrum shown in Figure 2. Figure 2 illustrates that optically thick Lyman-limit systems result in a measured flux in the \([880, 910]\) Å interval consistent with zero, making less likely the possibility that scattered light in the instrument is responsible for the residual flux shortward of 912 Å observed in the composite LBG spectrum.

In summary, none of the tests that we have performed gives us reason to believe that the residual flux shortward of 912 Å in Figure 1 is an artifact of systematics. Nevertheless, as discussed below, it would be prudent to view the detection with some skepticism until confirmed by higher quality spectra of individual objects. This is very difficult with existing instrumentation, but we expect that LRIS-B, the blue channel for LRIS optimized for the 3100–5500 Å wavelength range and soon to be commissioned on the Keck I telescope, will be ideally suited to making improved measurements on the much larger numbers of bright LBGs in our sample at \(z \approx 3.0.\)

3. THE EMERGENT FAR-UV SPECTRUM OF LBGs

One of the complications to the interpretation of the flux measurement above is that the opacity in the galaxies’ rest-frame Lyman continuum (in fact, for all spectral regions shortward of Ly\(\alpha\) emission) has a significant contribution from intervening material not directly associated with the galaxies. This contribution must be estimated accurately in order to infer the emergent spectrum of the star-forming galaxies. A common way to accomplish this is with models of intergalactic opacity based on column density distributions of Lyman series lines and the incidence of higher column density systems that contribute significant Lyman continuum opacity (e.g., Lyman-limit systems). The distribution functions, obtained from QSO absorption line surveys, are used to estimate the opacity of the IGM as a function of observed wavelength for objects at a given redshift (e.g., Madau 1995; Bashy, Charlot, & Geoffroy 1999). For our present purposes, we have opted to use a more direct empirical method that bypasses the need to model the opacity via fits to observed distribution functions. We have formed a composite QSO spectrum by combining spectra obtained for surveys of intervening Lyman-limit systems (see Sargent et al. 1989; Stengler-Larrea et al. 1995) of QSOs in the same range of redshift as the galaxies considered above. The spectra were chosen from among more than 100 QSOs in the redshift range \(2.75 \leq z \leq 4.10,\) all observed using the Palomar 200 inch telescope and Double Spectrograph; the spectral resolution in the 3150–4700 Å range was 4 Å. The composite spectrum, which is effectively an average over 15 lines of sight for QSOs with a mean redshift \((z_{\text{QSO}}) = 3.47 \pm 0.14,\) has been scaled to the composite LBG spectrum, rebinned to a similar resolution, and overplotted on Figure 1. Note the

---

**TABLE 2**

| Flux       | LGBs  | QSOs   |
|------------|-------|--------|
| \([880, 910]\) | \(0.19 \pm 0.04\) | \(0.50 \pm 0.03\) |
| \([1060, 1170]\) | \(1.79 \pm 0.03\) | \(1.86 \pm 0.02\) |
| \([1100]/(900)\): | \| | |
| uncorrected | \(9.4 \pm 2.0\) | \(3.7 \pm 0.2\) |
| corrected   | \(3.8 \pm 0.8\) | \(1.5 \pm 0.1\) |
| \([1500]/(900)\): | \| | |
| uncorrected | \(17.7 \pm 3.8\) | \(6.8 \pm 0.4\) |
| corrected   | \(4.6 \pm 1.0\) | \(1.9 \pm 0.1\) |

*All fluxes are in the arbitrary flux density units of Figure 1. Corrected quantities are those for which the statistical effects of intervening absorption have been removed using the procedure outlined in the text.*
similarity of the QSO and galaxy spectral energy distributions (SED) over the rest-wavelength range 1050–1700 Å, and that the Lyβ forest decrements in the rest-wavelength range 1050–1170 Å are equivalent for the QSO and galaxy spectra (the measured value of the \(D_A\) parameter [Oke & Korycansky 1982] is \(\approx 0.46\) for both).

The observed flux densities in the arbitrary units of Figure 1 are summarized in Table 2 for both the QSO and LBG spectra. To estimate the change in net opacity due to intergalactic material between 1100 Å (where it is obvious in both the galaxy and QSO spectra and is dominated by Lyβ line opacity from the forest) and rest-frame 900 Å, we adopt the intrinsic QSO spectral energy distribution shortward of 1050 Å suggested by Madau, Haardt, & Rees (1999), \(f_\nu \propto \nu^{-1.8}\). The observed change in the QSO continuum level between the [1060, 1170] Å interval and the [880, 910] Å interval is a factor of 3.7 ± 0.2; the intrinsic component of this flux decrement is estimated from the power-law assumption to be a factor of 1.5, so that the inferred flux decrement at 900 Å relative to that at 1100 Å due to intervening material is an additional factor of 2.5. Using this factor to correct the observed ratio \(f[1100]/f[900] = 9.4 ± 2.0\) for the galaxy spectrum, and accounting for the Lyβ line blanketing in the [1060, 1170] Å interval and a small difference in unabsorbed flux between 1500 and 1100 Å intrinsic to the galaxy SED (based on the mean color of the composite spectrum after correction of the observed G band for Lyβ line blanketing), one obtains an intrinsic flux density ratio for the LBGs of \(f[1500]/f[900] = 4.6 ± 1.0\). It is important to note that the observed ratio is \(f[1500]/f[900] \approx 17.7\), or a contrast of 3.1 mag on the AB scale.

Because of the effects of intergalactic absorption on the observations, a positive measure of Lyman-continuum flux becomes very rapidly more difficult with increasing redshift; the observation is probably impossible using present observational facilities by redshift \(z \sim 4.5\), despite higher system throughputs for ground-based spectroscopy—the intervening opacity is approximately 3 times higher, the sky background is about 3 times brighter, and typical galaxies are 2 times fainter than at \(z \sim 3\).

4. IMPLICATIONS

The flux density ratio \(f[1500]/f[900] = 4.6 ± 1.0\) obtained above is unexpectedly large for star-forming galaxies; it is similar to typical models of the UV SEDs of star-forming galaxies (e.g., G. Bruzual & S. Charlot 1996, private communication) without any Lyman-continuum self-absorption from \(H\ I\) in the galaxy. However, it must be realized that at present there are no direct measurements of the intrinsic amplitude of the stellar Lyman break, and we must rely exclusively on models. The model predictions depend sensitively on the initial mass function and stellar lifetimes at the very high mass end, and on the age of the star formation episode. The amplitude of the stellar Lyman limit for most spectral synthesis models (e.g., G. Bruzual & S. Charlot 1996, private communication; Leitherer et al. 1999) ranges from a factor of \(\sim 3\) to \(\sim 5.5\) over a plausible range of ages and initial mass functions. More recent models (e.g., Schaerer 1998), which include non-LTE effects, generally produce somewhat smaller break amplitudes than the LTE models that are used by the popular spectral synthesis programs, as small as a factor of 2.5 for constant star formation over periods of more than \(10^7\) yr (L. J. Smith & R. P. F. Norris, private communication). Adopting for the moment the assumption that the stellar energy distribution has an intrinsic Lyman discontinuity of a factor of 3, our result for \(f[1500]/f[900]\) implies that the fraction of UV ionizing photons escaping the galaxy is \(f_{esc} \gtrsim 0.5\).

Our definition of \(f_{esc}\) differs from a definition sometimes encountered elsewhere in the literature (e.g., Leitherer et al. 1995). By \(f_{esc}\) we mean the fraction of emitted 900 Å photons that escapes the galaxy without being absorbed by interstellar material divided by the fraction of 1500 Å photons that escapes. This is the quantity required to calculate the ionizing radiation emitted by Lyman-break galaxies from their well-constrained 1500 Å luminosity density. An alternate definition of \(f_{esc}\) is simply the fraction of emitted 900 Å photons that escapes (e.g., Leitherer et al. 1995); in this definition the 1500 Å normalization is omitted. Because perhaps only about 15%–20% of 1500 Å photons escape from typical LBGs without being absorbed by dust (e.g., Pettini et al. 1998; Adelberger & Steidel 2000), values of \(f_{esc}\) calculated under these two definitions will differ significantly.

The fraction of escaping Lyman-continuum photons is likely to be highly variable from galaxy to galaxy, depending (at least) on the morphological details of the galaxy-scale gaseous outflows that appear to be a ubiquitous signature of both high-redshift and low-redshift starburst galaxies (see Heckman 2000). As an example, consider the best far-UV spectrum of a galaxy (at any redshift) obtained to date, the gravitationally lensed LBG at \(z = 2.72\), MS 1512-cB58 (Pettini et al. 2000). In this case it would be surprising to find significant leakage of Lyman-continuum photons, given the extremely large covering fraction of optically thick (in the Lyman continuum) gas implied by the observed damped interstellar Lyβ line and several lines of low-ionization metallic species that are black at line center. On the other hand, the interstellar lines in the spectrum of the composite \(z = 3.4\) LBG presented above are less than half the strength of those in cB58; it is possible that this may be due to a smaller outflow covering fraction along our line of sight (or a smaller average velocity spread—it is difficult to tell the difference in spectra of 12.5 Å resolution), in which case a higher fraction of leaking Lyman-continuum photons would be expected. As mentioned in § 2, the galaxies chosen for the composite spectrum are drawn from the bluest quartile of the observed LBG population. While on average they have observed UV luminosities similar to the demagnified luminosity of cB58, they are a priori more likely to be younger and/or less dusty. Thus, it may be that, because of the selection effect for the high-redshift tail of the \(z \sim 3\) LBG distribution to be drawn from the bluest objects, they may be those “most likely to succeed” in getting Lyman-continuum photons out into the intergalactic medium.

Since there is now a published luminosity function for \(z \sim 3\) LBGs to apparent magnitudes of \(R \sim 27\), 2.5 mag fainter than \(P\) (Steidel et al. 1999), it is straightforward to calculate the contribution of LBGs to the general metagalactic radiation field at \(z \sim 3\) under the assumption that the composite spectrum is representative of the population as a whole. We use the measured ratio \(L(1500)/L(900) = 4.6 ± 1.0\) to convert the published LBG luminosity function (evaluated at a rest-frame wavelength close to 1500 Å) into a distribution of Lyman-continuum luminosities. This calculation is identical to that already carried out by Madau...
(2000), substituting a slightly different constant of proportionality. Integrating the Schechter (1976) function over all observed luminosities (down to 0.1 $L^*$), we obtain a comoving emissivity at 1 ryd of $1.2 \pm 0.3 \times 10^{26} \, h \, \text{ergs s}^{-1} \, \text{Hz}^{-1} \, \text{Mpc}^{-3}$ (for an Einstein–de Sitter cosmology) at $z \approx 3$, exceeding (according to Madau et al. 1999) the contribution from QSOs by a factor of about 5. Ignoring any contribution to the radiation field from “reprocessed” recombination and two-photon radiation (cf. Haardt & Madau 1996), and assuming an effective absorption distance of $\Delta z \approx 0.17$ for a Lyman-continuum photon at $z \approx 3$, the implied contribution of the LBGs to the metagalactic radiation field intensity is $J_\nu(912) \approx 1.2 \pm 0.3 \times 10^{-21} \, \text{ergs cm}^{-2} \, \text{Hz}^{-1} \, \text{sr}^{-1}$. This is very close to the value typically obtained from the QSO “proximity effect” (Bajtlik, Duncan, & Ostriker 1989; Scott et al. 2000, and references therein). Estimates of $J_\nu(912)$ from the proximity effect are subject to a variety of systematic uncertainties (see discussion in Rauch et al. 1997); independent upper limits have been placed on the value of $J_\nu(912)$ based on the lack of detection of fluorescent Ly$\alpha$ emission from Lyman-limit absorption clouds (Bunker, Marleau, & Graham 1998). $J_\nu(912) < 2 \times 10^{-21}$, but the validity of this limit is somewhat model-dependent. Given the inherent uncertainties in both our crude calculation and the measurements of $J_\nu(912)$, we do not believe that there is currently reason to be concerned about overproducing the UV background.

There has been extensive speculation in the literature as to whether QSOs are sufficient to provide the implied value of $J_\nu(912)$ at high redshift (e.g., Donahue & Shull 1987; Shapiro & Giroux 1987; Haardt & Madau 1996; Scott et al. 2000; Meiksin & Madau 1993; Madau et al. 1999). Most of the recent studies conclude that QSOs are marginally able to produce the proximity effect background at $z \approx 3$, but begin to have a serious problem by $z \approx 4$ due to the observed decreasing space density of bright QSOs (assumed to apply to faint QSOs as well) that has been observed by several groups (Kennicutt, Djorgovski, & de Carvalho 1995; Schmidt, Schneider, & Gunn 1995; SDSS collaboration). At $z \approx 3$, we have perhaps the best data for testing whether the QSO luminosity function at apparent magnitudes fainter than $R \approx 21$ is consistent with the extrapolated luminosity functions used in computing the QSO contribution to the background.3 For the LBG survey at $z \approx 3$ ($\sim 0.3$ deg$^2$), our observational selection of Lyman-break objects should be at least as complete for QSOs as it is for galaxies, since no attempt has been made to remove stellar objects from the sample, the SEDs of the galaxies and QSOs are quite similar, and the spectroscopic identification of objects with broad emission lines is more straightforward than for typical LBG spectra. Adopting the QSO luminosity function of Pei (1995), we should have found a total of $\approx 12$ spectroscopically identified QSOs in the redshift range $2.5 \leq z \leq 3.5$ over the apparent magnitude range $20.5 \leq R \leq 25.5$, taking into account the spectroscopic completeness and effective survey volumes as a function of apparent magnitude and redshift as described by Steidel et al. (1999). Our sample of 875 spectroscopically identified objects contains a total of eight QSOs with $2.5 \leq z \leq 3.5$, ranging in apparent magnitude from $R = 20.6$ to 24.8.

While a more careful analysis of the observed QSO density is beyond the scope of this paper, the point is that the QSO contribution to the metagalactic background is certainly no higher than has been estimated in recent analyses (cf. Haardt & Madau 1996). Steeper faint-end luminosity function slopes for QSOs at $z \approx 3$ are probably excluded by our survey data (cf. Haiman, Madau, & Loeb 1999).

5. SUMMARY AND DISCUSSION

We have presented observational evidence for significant Lyman-continuum emission over the rest-frame wavelength range 880–910 Å in the composite spectrum of Lyman-break galaxies at $z \approx 3.4$. After accounting for the effects of absorption due to intervening material in the spectral range of interest, we find an emergent flux density ratio of $f(1500)/f(900) = 4.6 \pm 1.0$. This ratio has been used to convert the observed far-UV luminosity function of LBGs into the luminosity density of Lyman-continuum photons at $z \approx 3$. Under the assumption that this spectral energy distribution is characteristic of the whole LBG population, LBGs provide a factor of $\sim 5$ times more hydrogen-ionizing photons than the estimated contribution from QSOs at the same redshifts. We have emphasized that the LBGs comprising the composite spectrum are drawn from the bluest quartile of intrinsic far-UV colors, so that they may be more likely than typical LBGs to exhibit significant escaping Lyman-continuum emission. However, adopting the steep $\alpha = -1.6$ far-UV luminosity function observed for LBGs (Steidel et al. 1999), intrinsically faint objects contribute a substantial fraction of the UV luminosity density. It may be that these faint objects are bluer on average than the $\sim L^*$ objects that comprise most of the LBG spectroscopic samples (cf. Meurer, Heckman, & Calzetti 1999), in which case the composite spectrum may be a good representation of the objects that dominate the UV luminosity density. Even if the distribution of rest-frame colors is independent of UV luminosity (in which case the composite spectrum would be representative of only $\sim 25\%$ of the LBGs), the implication is that LBGs contribute at least as many ionizing photons as QSOs at $z \approx 3$. We have presented preliminary results on the QSO density at faint magnitudes which emphasize that, if anything, the QSO contribution has been slightly overestimated.

A metagalactic radiation field with a contribution from young galaxies that is at least as large (at $z \approx 3$) as that from QSOs makes it much easier to understand how the intergalactic medium can remain highly ionized at redshifts $z \gtrsim 4$, where the QSO contribution to the radiation field decreases significantly (cf. Madau et al. 1999). While the UV luminosity function of LBGs is relatively poorly constrained at $z \approx 4$, and even more poorly constrained at $z \gtrsim 5$, there are indications that the comoving density of star-forming galaxies changes much more slowly than that of the QSOs at these redshifts (cf. Steidel et al. 1999), making it quite plausible that the universe is reionized by stars rather than active galactic nuclei (AGNs), and that stars play at least as important a role as QSOs in maintaining the high ionization level at later epochs.

While there is much to discuss regarding the possible implications of a metagalactic ionizing radiation field dominated by massive stars at $z \gtrsim 3$, we suggest that the results above be treated as preliminary until high-quality observations of individual galaxies exhibiting clear evidence for Lyman-continuum photon leakage become available. In

---

3 Unlike the QSO contribution, the LBG contribution to the metagalactic UV radiation field is based on a luminosity function where the full range of luminosities has been observed.
particular, it will be very interesting to explore the variation of Lyman-continuum leakage as a function of other galaxy properties (e.g., UV color, strength of stellar and interstellar absorption lines, UV or bolometric luminosity, etc.), since these are all factors of relevance for understanding the physics of rapidly star-forming galaxies at high redshifts, and their importance in affecting the hydrodynamics and chemical enrichment of the intergalactic medium. The limitation of the current data is largely instrumental: most spectrographs are blind in the near-UV. A new generation of near-UV optimized spectrographs on 8–10 m telescopes should allow wholesale observations of the Lyman continuum region among the large existing samples of UV-bright galaxies at $z \sim 3$.

We would like to thank our collaborators in the LBG survey project, Mark Dickinson, Mauro Giavalisco, and Alice Shapley, who played important roles in making this work possible. Informative discussions with Raul Jimenez, Linda Smith, Danny Lennon, and Stephane Charlot are gratefully acknowledged. C. C. S. and K. L. A. have been supported by grant AST 95-96229 from the US National Science Foundation and by the David and Lucile Packard Foundation.

REFERENCES

Adelberger, K. L., & Steidel, C. C. 2000, ApJ, in press (preprint astro-ph/0001126)
Bajtlik, S., Duncan, R. C., & Ostriker, J. P. 1988, ApJ, 327, 570
Bechtold, J., Weymann, R. J., Lin, Z., & Malkan, M. A. 1987, ApJ, 315, 180
Bershady, M. A., Charlton, J. C., & Geoffrey, J. M. 1999, ApJ, 518, 103
Bunker, A. J., Marleau, F. R., & Graham, J. R. 1998, AJ, 116, 2086
Calzetti, D. 1997, AJ, 113, 162
Donahue, M., & Shull, J. M. 1987, ApJ, 323, L13
Fullerton, A. W., et al. 2000, ApJ, 538, L43
Gunn, J. E., & Peterson, B. M. 1965, ApJ, 142, 1633
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Haiman, Z., Madau, P., & Loeb, A. 1999, ApJ, 514, 535
Heckman, T. M. 2000, Proc. R. Soc. London A, in press (preprint astro-ph/9912029)
Hurwitz, M., Jelinsky, P., & Dixon, W. V. 1997, ApJ, 481, L31
Kennellic, J. D., Djorgovski, S., & de Carvalho, R. 1995, AJ, 110, 2553
Leitherer, C., et al. 1999, ApJS, 123, 3
Leitherer, C., Ferguson, H. C., Heckman, T. M., & Lowenthal, J. D. 1995, ApJ, 454, L19
Madau, P. 1995, ApJ, 441, 18
———. 2000, Philos. Trans. R. Soc. London A, 358, 2221
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Meiksin, A., & Madau, P. 1993, ApJ, 412, 34
Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, ApJ, 521, 64
Miralda-Escude, J., & Ostriker, J. 1990, ApJ, 350, 371
Oke, J. B., & Korycansky, D. G. 1982, ApJ, 255, 11
Oke, J. B., et al. 1995, PASP, 107, 375
Pei, Y. C. 1995, ApJ, 438, 623
Pettini, M., Kellogg, M., Steidel, C. C., Dickinson, M., Adelberger, K. L., & Giavalisco, M. 1998, ApJ, 508, 539
Pettini, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M. 2000, ApJ, 528, 96
Rauch, M., Miralda-Escude, J., Sargent, W. L. W., Barlow, T. A., Weinberg, D. H., Hernquist, L., Katz, N., Cen, R., & Ostriker, J. P. 1997, ApJ, 481, 601
Sargent, W. L. W., Steidel, C. C., & Boksenberg, A. 1989, ApJS, 69, 703
Sargent, W. L. W., Young, P. J., Boksenberg, A., & Tyler, D. 1980, ApJS, 42, 41
Schaerer, D. 1998, ASP Conf. Ser. 131, Boulder-Munich II: Properties of Hot, Luminous Stars, ed. I. D. Howarth (San Francisco: ASP), 310
Schechter, P. 1976, ApJ, 203, 297
Schmidt, M., Schneider, D. P., & Gunn, J. E. 1995, AJ, 110, 68
Scott, J., Bechtold, J., Dobrozycki, A., & Kulkarni, V. P. 2000, ApJS, 130, 67
Shapiro, P. R., & Giroux, M. L. 1987, ApJ, 321, L107
Songaila, A., Cowie, L. L., & Lilly, S. J. 1990, ApJ, 348, 371
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, 532, 170
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
Steidel, C. C., & Hamilton, D. 1993, AJ, 105, 217
Steidel, C. C., & Sargent, W. L. W. 1989, ApJ, 343, L33
Stengler-Larrea, E. A., et al. 1995, ApJ, 444, 64
Walborn, N. R., & Bohlin, R. C. 1996, PASP, 108, 477