AN IONIZING ULTRAVIOLET BACKGROUND DOMINATED BY MASSIVE STARS

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ABSTRACT

We discuss the implications of a stellar-dominated UV background at high redshifts for the star formation history of Lyman break galaxies (LBGs) and the thermal and ionization state of the intergalactic medium (IGM). The composite spectrum of 29 LBGs evaluated by Steidel et al. at $z=3.4$ can be well fitted by a stellar population with ongoing star formation, a Salpeter initial mass function, modest or negligible dust reddening, and no intrinsic H i photoelectric absorption. Fading starbursts in which star formation has ceased for 10$^7$ yr or more cannot reproduce the observed flux shortward of 1 ryd. The small H i optical depth in LBGs suggests that the neutral gas from which stars form is most likely contained in compact clouds of neutral gas with small covering factor. The escape fraction of H-ionizing photons must be close to 100% for the observed sample of LBGs. The spectrum of ionizing photons produced by a stellar population with ongoing star formation is similar to that of QSOs between 1 and 3 ryd but becomes softer between 3 and 4 ryd and drops sharply shortward of 4 ryd. A galaxy-dominated UV background appears inconsistent with the observed He ii/H i opacity ratio at $z=2.4$ but might be able to explain the Si iv/C iv abundances measured at $z>3$ in QSO absorption spectra. A scenario may be emerging where star-forming galaxies reionize intergalactic hydrogen at $z>6$ and dominate the 1 ryd metagalactic flux at $z>3$, with quasi-stellar sources taking over at lower redshifts. If the large amplitude of the H-ionizing flux estimated by Steidel et al. is correct, hydrodynamical simulations of structure formation in the IGM within the cold dark matter paradigm require a baryon density (to explain the observed opacity of the Ly$\alpha$ forest in QSO absorption spectra) that is similar to or larger than that favored by recent cosmic microwave background experiments and is inconsistent with standard nucleosynthesis values.

Subject headings: cosmology: theory — intergalactic medium — quasars: absorption lines

On-line material: color figures

1.INTRODUCTION

The strength and spectrum of the UV ionizing background at high redshift and the nature of the sources that reionized the hydrogen component of the intergalactic medium (IGM) are two of the big outstanding questions in observational cosmology. QSOs and star-forming galaxies have long been considered the two prime candidates. It has been argued that QSOs may fall short of producing a metagalactic flux as high as that inferred from the proximity effect at high redshift (Bechtold 1994; Giallongo et al. 1996; Cooke, Espey, & Carswell 1997; Scott et al. 2000) since their space density declines rapidly at early epochs

2. IMPLICATIONS FOR THE STAR FORMATION HISTORY

The most striking feature of the composite spectrum of Steidel et al. (2001) is the apparent lack of a significant drop at the Lyman limit. Stars with effective temperatures $\lesssim$30,000 K have a strong intrinsic break at the Lyman edge. The composite spectrum shortward of 1 ryd is thus dominated by O stars with masses $\gtrsim 20 \ M_\odot$ and lifetimes $\lesssim 10^7$ yr. Note that the signatures of O stars have already been detected at longer wavelengths (Pettini & Adelberger 2001) of flux beyond the Lyman limit (with no significant indication of a break at 912 Å) in a composite spectrum of 29 LBGs at $z=3.4$ thus comes as a surprise.

In this Letter, we assess the significance of the Steidel et al. (2001) findings by comparing their spectrum to model spectra calculated with the population synthesis code STARBURST99 (Leitherer et al. 1999). We discuss the implications of this result for the star formation history and gas content of these galaxies, for the spectrum of the UV background, for the cosmological reionization, and for the baryon content of the universe.
were calculated with STARBURST99 (Leitherer et al. 1999). With an SMC extinction curve and was included. Steidel et al. (2001).

The absence of a significant intrinsic H I photoelectric opacity in the spectra of LBGs implies that those ionizing photons that avoid absorption by dust can escape the galaxy unimpeded. After correction for intergalactic absorption, the mean ratio of emergent flux density at (rest frame) 900 and 1500 Å is equal to 0.22 ± 0.05 according to Steidel et al. (2001). Assuming this ratio is typical of all LBGs at z ≈ 3 (this might not be true since the composite spectrum is drawn from the bluest quartile of the LBG population), Steidel et al. estimate $J_{1500} = 1.2 ± 0.3$ for the galaxy contribution to the ionizing flux at the Lyman limit (here $J_{1500}$ is measured in units of $10^{21}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$). This is about a factor of 4 larger than the contribution of QSOs at this redshift. As pointed out by Steidel et al., the blue colors of the subsample of LBGs used for the composite spectrum suggests modest or no reddening and thus that little or no absorption by dust occurs in these galaxies. A very large fraction of, if not all, H-ionizing photons seem to be able to escape from this particular subsample of LBGs. This has important implications for attempts to estimate the H-ionizing flux due to the first massive stars, which presumably form in the shallow potentials predicted to be present in large numbers well before z = 6 in standard hierarchical cosmogonies (Madau et al. 1999). Note that because of the much smaller dust content, a comparison of the composite spectrum of Steidel et al. with the UV spectra of low-redshift starbursts, as observed, e.g., by Leitherer et al. (1995) and Hutz, Jeninski, & Dixon (1997), is not straightforward.

**Fig. 1.—** Thin solid curve: Composite spectrum of 29 LBGs at $z = 3.4$ from Steidel et al. (2001). Thick solid curve: Synthetic spectrum of a stellar population with continuous star formation and Salpeter IMF. A modest amount of reddening with an SMC extinction curve and $E_{B-V} = 0.03$ was included. Dashed curve: Synthetic spectrum of an instantaneous starburst after 10$^7$ yr. The model spectra were calculated with STARBURST99 (Leitherer et al. 1999).[See the electronic edition of the Journal for a color version of this figure.]

3. THE NEUTRAL HYDROGEN DISTRIBUTION OF LYMAN BREAK GALAXIES

If star formation in LBGs is indeed continuous and lasts for about 100 Myr, there should be a substantial amount of neutral hydrogen present in these systems. The LBGs in the Steidel et al. (2001) sample have typical star formation rates of $M_* = 10^{-5} - 10^{-3}$ $M_\odot$ yr$^{-1}$. They should thus contain $M \approx 10^{10} (30 M_\odot$ yr$^{-1} M_*/$yr$)$ $M_\odot$ of cold gas if the cold gas to stellar mass ratio were of order unity. Taking a typical half-light radius of 2 kpc as a characteristic size and assuming that the cold gas is distributed homogeneously, the typical density and column density should be $\sim 3(M/10^{10} M_\odot)/(r/2$ kpc)$^{-3}$ cm$^{-3}$ and $2 \times 10^{19} (M/10^{10} M_\odot)(r/2$ kpc)$^{-2}$ cm$^{-2}$, respectively. These values are higher than those of damped Lyα systems, and a large H I optical depth would therefore be expected.

A luminosity in ionizing photons of at least $10^{44.5} \times (M/10^{10} M_\odot)(r/2$ kpc)$^{-3}$ ergs s$^{-1}$ is needed to keep this large amount of gas photoionized. The required luminosity is a factor of 10–30 higher than that of the LBGs in the sample. Therefore, either the LBGs should have a small cold-neutral gas mass to stellar mass ratio in their luminous regions or the cold gas must be contained in small compact regions with small covering factor.

4. THE UV ESCAPE FRACTION OF GALAXIES AND THE REDSHIFT EVOLUTION OF THE UV BACKGROUND

**Fig. 2.—** He II line-blanketing opacity as a function of redshift for a UV background dominated by QSOs and stars. The different curves show the optical depth for a stellar contribution to the flux at 1 r yd equal to (from bottom to top) 0, 0.5, 1.5, 2.5, and 5 times that of QSOs. The H I optical depth is fixed to $\tau_{HI} = 0.0038(1 + z)^{0.6}$, while the ionizing flux at $z = 2.4$ from QSOs only is $J_{13} = 0.3$ in all cases (Haardt & Madau 1996).[See the electronic edition of the Journal for a color version of this figure.]

The absence of a significant intrinsic H I photoelectric opacity in the spectra of LBGs implies that those ionizing photons that avoid absorption by dust can escape the galaxy unimpeded. After correction for intergalactic absorption, the mean ratio of emergent...
then increases with increasing stellar contribution to the total flux. The values chosen for the stellar contribution would be realized, e.g., if the flux at 900 Å due to the integrated spectral energy distributions of massive stars, which may or may not be modified by the absorption of dust, were on average a factor $f_{\text{stell}}/f_{\text{cont}} = 0.22$ smaller than the flux at 1500 Å and if a fraction of 0%, 10%, 30%, 50%, and 100% (top to bottom) of the H-ionizing photons that avoided a possible absorption by dust were also not absorbed by neutral hydrogen and actually escaped the galaxy.

A UV background dominated by stars is clearly inconsistent with the observed ratio of He II and H I optical depth at $z \sim 2.4$. At $z \sim 2.4$, the average ratio of the emergent fluxes at 900 and 1500 Å must be about a factor of 10 smaller than that of the Steidel et al. (2001) subsample at $z \sim 3.4$. If the results of Steidel et al. were representative of the entire LBG population at this redshift, then either the integrated stellar spectral energy distribution of LBGs or the average fraction of H-ionizing photons avoiding absorption by dust but not by neutral hydrogen would have to evolve very rapidly with decreasing redshift.

5. A UV BACKGROUND DOMINATED BY STELLAR SOURCES AT HIGH REDSHIFT

Having found a simple model that reproduces the observed spectrum in the wavelength range $\lambda\lambda 870$–1600, we can now extrapolate the UV spectrum to shorter wavelengths. The result is shown in Figure 3. We have assumed the full range of dust optical depth as reported by Steidel et al. (1999) with no dependence of dust optical depth on UV luminosity together with an SMC reddening curve (absorption only, no scattering; Pei 1992). We also assumed that the null detection of H I absorption due to the ISM in the Steidel et al. sample is representative of all LBGs. Just beyond the Lyman limit the spectrum is very similar to that of a typical QSO, even somewhat harder than the canonical $-1.8$ power law (Zheng et al. 1998). It is only at wavelengths shorter than $\lambda 400$ that it softens significantly compared to a QSO spectrum. Beyond the He II Lyman edge at 4 ryd there is a strong break.

The similarity to a QSO spectrum just beyond 1 ryd may explain the already high temperatures of $10^7$ K at $z > 3$ (Haehnelt & Steinmetz 1998; Schaye et al. 2000). A UV background that is progressively dominated by O stars may also be the solution to the increasing Si IV/C IV ratio with increasing redshift observed in metal absorption systems of intermediate column densities (Songaila & Cowie 1996; Giroux & Shull 1997; Boksenberg, Sargent, & Rauch 2001).

How different could the integrated stellar spectrum be? The upper cutoff of the IMF and the metallicity will strongly affect how far the spectrum extends into the far-UV (Tumlinson & Shull 2000; Bromm, Kudritzki, & Loeb 2001; Oh, Haiman, & Rees 2001). We have assumed an upper cutoff of 100 $M_\odot$ and solar metallicity. The dust opacity in the far-UV depends on smaller grains than usually probed by reddening analyses and is rather uncertain. In the model of Pei et al. (1992) for the SMC opacity used here, the dust opacity drops shortward of 1000 Å. This makes the spectrum bluer, not redder, at wavelengths shorter than 1000 Å. The stellar spectra of massive stars with strong mass loss are complex and require non-LTE calculations including the effect of stellar wind outflow and spherical extension. In particular, the strength of the 4 ryd break depends significantly on metallicity, mass-loss rates, and details of the modeling (Kudritzki 2000; Pauldrach, Hoffmann, & Lennon 2001).

6. THE BARYON FRACTION OF THE UNIVERSE

One interesting consequence of the large amplitude of the UV background suggested by Steidel et al. (2001) is the implied conflict of the Lyα opacity measurements in QSO spectra with the nucleosynthesis constraint for the baryon density. The optical depth for Lyα scattering of the photoionized IGM scales as $(Q_{\text{emitters}}/Q_{\text{ionizers}}) \propto 10^{-1.8} T^{-0.7} \Gamma^{-1}$, where $\Gamma$ is the photoionization rate, $T$ is the gas temperature, $Q(z)$ is the Hubble constant at redshift $z$, $\Omega_b$ is the baryon density parameter, and $h$ is the present-day Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. The investigation of Rauch et al. (1997a, 1997b) implies that for a nucleosynthetic value of $\Omega_b h^2 = 0.019$ (Burles & Tytler 1998), the Lyα opacity can be matched if $\Gamma \sim 5 \times 10^{-13}$ s$^{-1}$. For a spectrum $f_\nu \propto \nu^{-1.8}$, this corresponds to an ionizing flux $J_{21} = 0.12$. The large value of $J_{21} = 1.2 \pm 0.3$ suggested by Steidel et al. implies instead $\Omega_b h^2 \approx 0.06$. The D/H measurements are therefore in strong conflict with the Lyα opacity measurements if the standard nucleosynthesis calculations, the value of $J_{21}$ suggested by Steidel et al., and the density/temperature distributions suggested by hydrodynamical simulations are correct. There may also be a contribution to the H-ionizing background from faint Lyα emitters with weak stellar continuum flux as suggested by Kudritzki et al. (2000).

In Figure 4, we have compiled from the literature a number...
of values for Ω, h^2 implied by the measured Lyα opacity assuming J_{Lyα} = 0.6, as may be appropriate if LBGs with redder spectra than those in the Steidel et al. sample had a significantly smaller ratio of the emergent flux at 900 and 1500 Å. The values at z = 3 are from Rauch et al. (1997a), Gnedin (1998), Nusser & Haehnelt (2000), and Theuns et al. (2000), and those at z = 2 are taken from Cen et al. (1994) and Hernquist et al. (1996). We have scaled all values to a temperature of 15,000 K at z = 3 and 11,000 K at z = 2, as suggested by the temperature determination of the IGM by Schaye et al. (2000). All values for Ω, scale proportional to J_{Lyα} and T^0.35. We also show the nucleosynthesis constraint from the D/H measurement as given by Burles & Tytler (1998) and the combined constraints from the microwave background (CMB) experiments BOOMERANG and MAXIMA (Jaffe et al. 2001).

7. DISCUSSION AND CONCLUSIONS

We have shown that the detection of flux beyond the Lyman limit from LBGs is most easily explained as being due to the O stars present in a star-forming region with ongoing star formation, a Salpeter IMF, modest or negligible reddening, and negligible absorption due to H i in the local ISM. Fading starbursts in which star formation has ceased for 10^7 yr or more cannot reproduce the observed flux shortward of 1 ryd. The small H i optical depth cannot be due to photoionization. The cold neutral gas from which the stars form must be contained in compact small regions with small covering factor.

The resulting ionizing background will be dominated by O stars shortward of the Lyman limit and is as hard as a QSO spectrum between 1 and 3 ryd. Shortward of 3 ryd the spectrum is softer than a QSO spectrum, and there is a strong drop shortward of 4 ryd. A consistent picture seems to emerge where the hydrogen of the universe is reionized by stars at z > 6, while the reionization of helium is due to QSOs and is delayed to z ~ 4 or 3. The contribution of stars to the ionizing UV background is equal to or larger than that of QSOs at least up to z ~ 3. At smaller redshift, the ratio of He ii and H i opacity and the observed Si iv/C iv ratios in the associated metal absorption systems of intermediate column density QSO absorption systems argue for a UV background dominated by QSOs. This requires a rapid evolution of the integrated stellar spectral energy distribution of LBGs or of the average fraction of H-ionizing photons avoiding absorption by dust but not by neutral hydrogen.

The amplitude of the UV background inferred from the composite spectrum of Steidel et al. (2001) makes the measurements of the opacity of the Lyα forest in QSO absorption spectra inconsistent with D/H measurements if the spectrum is representative for all LBGs, the nucleosynthesis calculations for D/H are correct, and the hydrodynamical simulations reproduce the temperature/density distribution of the IGM correctly. The inferred value for Ω, is similar to that indicated by the CMB experiments BOOMERANG and MAXIMA if J_{Lyα} = 0.4–0.6.

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