ARE THERE ENOUGH IONIZING PHOTONS TO REIONIZE THE UNIVERSE BY $z \approx 6$?

NICKOLAY Y. GNEDIN$^{1,2,3}$

Received 2007 September 20; accepted 2007 November 29; published 2007 December 19

ABSTRACT

The number of ionizing photons per baryon as a function of redshift is estimated from the plausible extrapolation of the observed galaxy UV luminosity function and the latest results on the properties of the escape fraction of ionizing radiation. If the escape fraction for low-mass galaxies ($M_{\text{TOT}} \leq 10^{11} M_\odot$) is assumed to be negligibly small, as indicated by numerical simulations, then there are not enough ionizing photons to reionize the universe by $z = 6$ for the cosmology favored by the Wilkinson Microwave Anisotropy Probe (WMAP) third-year results, while the WMAP first-year cosmology is marginally consistent with the reionization requirement. The escape fraction as a function of galaxy mass would have to be constant to within a factor of 2 for the whole mass range of galaxies for reionization to be possible within the WMAP third-year cosmology.

Subject headings: cosmology: theory — galaxies: formation — intergalactic medium — large-scale structure of universe

Online material: color figures

1. INTRODUCTION

Studies of cosmic reionization—especially theoretical ones—have never been considered a “photon-starved” field. Theorists always felt free to select the emissivity of the ionizing sources, usually quantified by the escape fraction of ionizing radiation, to adjust the reionization redshift to their choosing. This approach was, indeed, justified in the earlier studies, since until recently limited knowledge existed on the reasonable values for the escape fraction at high redshifts. However, the latest observational (Giallongo et al. 2002; Fernández-Soto et al. 2003; Shapley et al. 2006; Chen et al. 2007) and numerical (Razoumov & Sommer-Larsen 2006, 2007; Gnedin et al. 2007) studies finally begin to converge on the values and evolution of the escape fraction of ionizing radiation and on the relative escape fraction between the far-UV and Lyman limit. Three properties of the escape fraction are particularly important for reionization studies: (1) the value of the escape fraction is small (a few percent at most), which is an order of magnitude smaller than that assumed in some reionization modeling, (2) it is weakly dependent on the galaxy mass or star formation rate for large galaxies, and (3) it drops prodigiously for dwarf galaxies. The first two properties are reproduced in all recent studies, both observational and theoretical, and therefore are rather robust. The last feature of the escape fraction has only been seen in simulations of Gnedin et al. (2007) and is indicated by measurements of Fernández-Soto et al. (2003), because other simulations and observational studies do not yet have either numerical resolution or sensitivity to resolve dwarf galaxies.

Another important observational advance that places the study of reionization on a much more quantitative footing is the observational determination of the galaxy UV luminosity function down to well below $L_*$ at $z \gtrsim 6$. Since it is not possible to give a comprehensive review of all observations in this Letter due to space limitations, I refer the reader to the recent work by Bouwens et al. (2007), who give a detailed review of the current status of existing observational data. While the data for the galaxy luminosity function during the reionization era ($z > 6$) are still sparse, the plausible extrapolation of the observed $z \approx 6$ luminosity functions to higher redshifts can be used to predict the global production of the ionizing radiation to at least within a factor of 2–3, i.e., more than an order of magnitude improvement over the previous, purely theoretical assumptions.

Of course, the most accurate models are only possible with the large-box and high-resolution cosmological simulations, which model in detail the emission of ionizing photons in high-redshift galaxies and quasars, the propagation of ionizing radiation in the expanding universe, and absorption of that radiation at cosmic ionization fronts and Lyman limit systems. But even the simplest balance of the available ionizing photons and the number of atoms that need to be ionized before the end of reionization at $z = 6$, as required by the observed transmitted flux in the spectra of high-redshift quasars discovered by the Sloan Digital Sky Survey (SDSS) collaboration (Fan et al. 2006), is a useful exercise after the recent improvements in our understanding of the sources of reionization.

2. RESULTS

In order to compute the total number of ionizing photons available for reionizing the universe at any given redshift, the observed luminosity functions need to be extrapolated to earlier redshifts. Such extrapolation is, of course, not unique. However, since the mass function of dark matter halos can be computed sufficiently precisely in a given cosmology at any redshift, the extrapolation of the luminosity function to $z > 6$ can be made reliably if the relationship between the galaxy luminosity and the mass of its dark matter halo can be established.

While such a relationship is unlikely to be a simple function, models that assume a one-to-one correspondence between the galaxy luminosity and the halo mass provide remarkably good fit to a variety of observational tests (Conroy et al. 2006). Thus, as a simple and crude approximation, it is instructive to assume such a relationship between the galaxy UV luminosity $L_{\text{UV}}$ for the high-redshift galaxies as well.

In a given cosmology, this relationship between the total mass of a dark matter halo $M_{\text{TOT}}$ and the luminosity of a galaxy
hosted in that halo $L_{\text{UV}}$ can be obtained by matching the cumulative mass and luminosity functions,

$$n(>L_{\text{UV}}) = f_{\text{ON}} n(>M_{\text{TOT}}),$$

where $f_{\text{ON}}$ is the fraction of dark matter halos that actually host a source of luminosity $L_{\text{UV}}$. For nonbursting sources, $f_{\text{ON}} \approx 1$. While there exists no compelling observational evidence that high-redshift galaxies are particularly bursty (Steidel et al. 1999; Pettini et al. 2001; Shapley et al. 2001), I keep this parameter for the sake of generality, while adopting $f_{\text{ON}} = 1$ as a fiducial value. As I show below, large variations in this parameter do not substantially affect the conclusions of this Letter because the parameter $f_{\text{ON}}$ only affects the particular form for the extrapolation of the observed luminosity functions to higher redshifts, but not the rate of emission of ionizing photons at redshifts $z \lesssim 6$, where the luminosity functions are actually measured.

The mass-luminosity relations derived from equation (1) are shown in Figure 1 for the four values of redshift for which Bouwens et al. (2007) give the parameters of the Schechter function fits, assuming the best-fit cosmology for the combination of WMAP third-year data and the Large Red Galaxies part of the SDSS survey (WMAP3; Spergel et al. 2007). Unfortunately, the derived relation between the UV luminosity (as expressed by the AB absolute magnitude at 1600Å, $M_{1600}$) and the total halo mass is redshift-dependent and thus cannot be easily extrapolated to higher redshifts. However, a simple correction of the UV luminosity by a factor of $C$ and the total mass by a factor of $C^3$ with $C(z) = (1 + z)/7$ eliminates most of the redshift dependence for halos more massive than $\sim 3 \times 10^{10} M_\odot$, as shown in Figure 2. As I discuss below, these low-mass halos contribute almost nothing to the ionizing photon budget and so are unimportant for the purpose of this Letter. Throughout the rest of this Letter, I use the average relation marked by a black line in Figure 2.

The relation between the UV and ionizing luminosities is quantified by the relative escape fraction, $f_{\text{esc, rel}} = f_{\text{esc}}(1600)/f_{\text{esc}}(912)$, and the value of the intrinsic ratio of stellar luminosities at these two wavelengths, $r_{\text{int}} = (L_{1600}/L_{912})_{\text{int}}$. For the escape fraction at the Lyman limit I adopt the results of Gnedin et al. (2007), who found that in high-resolution simulation of galaxies with radiative transfer escape fractions for larger galaxies are of the order of a few percent, consistent with observational determinations, but little (if any) radiation escapes from small galaxies. Thus, for the relative escape fraction as a function of galaxy mass I adopt the following form:

$$f_{\text{esc, rel}}(M) \approx \begin{cases} 0.15 \frac{1}{s_{\text{min}}} & \text{if } M_{\text{TOT}} > 5 \times 10^{10} M_\odot, \\ \text{otherwise}. & \end{cases}$$

This form is consistent with observational measurements of the relative escape fraction (e.g., Shapley et al. 2006) for massive galaxies. The drop in the escape fraction is also indicated in observations of Fernández-Soto et al. (2003), but the characteristic transition occurs at a factor of 10 higher star formation rate, which would correspond to a higher characteristic mass. The adopted value of $5 \times 10^{10} M_\odot$ therefore likely biases the estimate production of ionizing photons up. Here, as well as in the rest of the Letter, all uncertain quantities are chosen so as to ensure that my estimate for the total number of ionizing photons is likely to be an overestimate, rather than an underestimate. I return to the uncertainty of the main result in § 3.

In the Gnedin et al. (2007) simulations, the relative escape fraction of low-mass galaxies ($M_{\text{TOT}} < 5 \times 10^{10} M_\odot$) never exceeds about 0.01 and is often much lower, so I adopt $s_{\text{min}} = 0.05$ as my fiducial value. I consider the effect of parameter $s_{\text{min}}$ in § 3. Using the mass-to-light matching from Figure 2, the mass dependence can also be recast as the luminosity dependence.

For the intrinsic break, I adopt a value of $r_{\text{int}} \approx 3$ (Shapley et al. 2006). However, Siana et al. (2007) argue for a larger value for the intrinsic break, $r_{\text{int}} \approx 6$, and that larger value is...
also consistent with Starburst99 spectral synthesis models (Leitherer et al. 1999). Here I again adopt a lower value as a fiducial number so as not to underestimate the total number of ionizing photons.

With the above assumption, the total emission rate density of the ionizing photons at a given redshift \( z \) can now be expressed as

\[
\dot{n}_p = \int dL_{1600} \frac{f_{\text{esc},\text{red}}}{r_{\text{int}}} \frac{L_{1600}}{\langle E \rangle} \frac{dn}{dL_{1600}},
\]

where \( \langle E \rangle \) is the average energy of a photoionizing photon (which I take to be 22 eV, consistent with typical spectra of starburs; Leitherer et al. 1999) and \( dn/dL_{1600} \) is the comoving UV luminosity function obtained from the halo total mass function using the mass-to-light ratio from Figure 2. The total number of ionizing photons per baryon at time \( t \) is then \( N_{\text{ph}}(t) = n_p(t) n_b \), where \( n_b \approx 2.5 \times 10^{-7} \text{ cm}^{-3} \) is the comoving number density of baryons.

It is important to emphasize here that equation (2) does not depend on the star formation rate in high-redshift galaxies, but only on their observed UV luminosities. Thus, this approach completely circumvents the poorly known conversion of the observed UV luminosity to the star formation rate and uncertainties due to (possible) variations in the initial mass function (IMF), dust contents and composition, etc.

An additional complication in this estimate is introduced by a possible contribution to the ionizing background from high-redshift quasars.

Fortunately, the quasar luminosity function is reasonably well known all the way to \( z \approx 5 \) (Hopkins et al. 2007). Using the fitting code provided by Hopkins et al. (2007), the emission rate density of ionizing radiation from quasars can be estimated at a range of redshifts \( 4 < z < 6 \). Such an estimate agrees remarkably well with an earlier estimate by Madau et al. (1999); for example, the Hopkins et al. (2007) fit at \( z = 5 \) results in \( \log (n_p) \approx 50.5 \), while the Madau et al. (1999) estimate at that redshift is \( \log (n_p) \approx 50.6 \). At \( z = 4 \) both estimates give the same value of \( \log (n_p) \approx 50.8 \). These values are also in excellent agreement with several other previous estimates and upper limits (Fan et al. 2001; Meiksin 2005; Srinovsky & Wyithe 2007).

The extrapolation of the Hopkins et al. (2007) luminosity function to \( z > 5 \) is, of course, highly uncertain. In order to approximately account for possible uncertainties, I consider two different extrapolations: the “lower” one simply uses the Hopkins et al. (2007) best-fit model to compute the quasar luminosity function at any redshift; the “higher” extrapolation multiplies the lower one by a factor of \( [1 + z]/6 \) (chosen arbitrarily), greatly increasing quasar abundance at higher redshifts.

The resultant photon-to-baryon ratio is shown in Figure 3 for two adopted sets of cosmological parameters: the WMAP3 cosmology introduced above and the best-fit values for the pure \( \Lambda \)CDM model from the first year WMAP data (WMAP1; Spergel et al. 2003).\(^6\) As can be seen, the quasar contribution is smaller than the one from galaxies by at least an order of magnitude, and so its large uncertainty is not that important. The effect of high-redshift galaxies being bursty (\( \dot{U}_{\text{int}} < 1 \) in eq. [1]) does not change the main conclusion of this Letter substantially; setting \( f_{\text{on}} = 0.1 \) lowers \( N_{\text{ph}}(z = 6) \) by about 40% and, in fact, exacerbates the discrepancy with the reionization requirement.

\(^6\) \( \Omega_m = 0.27, h = 0.72, n_s = 0.99, \sigma_8 = 0.90 \).
where \( \bar{\delta} \) is the average overdensity in that region, and \( C_p \) is the recombination clumping factor in that region (Kohler et al. 2007), \( C_p = \langle R(T) \rangle / \langle R(T) \rangle_{\text{fid}} \).

Since the definition of the escape fraction of ionizing radiation from Gnedin et al. (2007) accounts for all local absorption, including high-density gas inside a galaxy halo, which dominates the clumping factor, \( C_p \) cannot be large in the general intergalactic medium (IGM). More than that, the conclusion that reionization is complete by \( z \approx 6 \) comes primarily from the observations of the SDSS quasars (Fan et al. 2006 and references therein). The transmitted flux at \( z \approx 5.5 \) comes mostly from the centers of large voids, where \( (1 + \bar{\delta}) \approx 0.1 \) and \( C_p \leq 10 \). Equation (3) then implies that less than 2 ionizing photons per baryon (outside the virial radii of ionizing sources) are needed to satisfy the observational requirements. Of course, if the local absorption inside the virial radius (characterized by a large clumping factor \( C_p \)) is included, the required number of ionizing photons per baryon will be much higher; but then a correspondingly larger value for the escape fraction (which excludes local absorption) should be adopted. That estimate is also consistent with the conclusion by Miralda-Escudé (2003), who estimated that \( dN_{\gamma b}/(Hdt) \approx 7 \) for \( 6 < z < 9 \), which translates into \( N_{\gamma b} \leq 2.5 \) if the contribution of sources beyond \( z \approx 9 \) is unimportant.

Thus, a requirement

\[
1 < N_{\gamma b}(z = 6) < 3
\]

appears to be a sensible criterion for the reionization of the universe by \( z \approx 6 \). The same condition has also been obtained by Bolton & Haehnelt (2007) from extrapolating the production rate of ionizing photons required to fit the observed evolution of the mean opacity of the Ly\( \alpha \) forest to \( z = 6 \).

Thus, the WMAP3 cosmology is marginally sufficient to satisfy the condition (4d), while the WMAP3 universe is well short of the needed amount of ionizing radiation at \( z \approx 6 \) by at least a factor of 2 (and, perhaps, as much as a factor of 10 if the value for the intrinsic break \( r_{\text{min}} \) is closer to 6 than to 3, and the transition to low escape fraction occurs at \( 5 \times 10^{11} M_\odot \) rather than at \( 5 \times 10^{9} M_\odot \)).

This somewhat unexpected result crucially depends on the main conclusion of Gnedin et al. (2007) that the escape fraction is very small for low-mass galaxies. That conclusion is consistent with the observational measurements of the escape fraction by Fernández-Soto et al. (2003) and our knowledge of dwarf galaxies in the local universe, which are known to have large gas fractions and \( \text{H I} \) extend that exceeds the extend of the stellar disk. On the other hand, as Figure 4 shows, if the escape fraction is independent of the galaxy mass (\( s_{\text{mean}} = 1 \)), the WMAP3 cosmology comfortably falls into the reionization requirement with \( N_{\gamma b}(z = 6) \approx 1.5 \).

It is therefore important to have the measurements of the escape fraction extended to even fainter galaxies and the result of Gnedin et al. (2007) verified with higher resolution simulations and different numerical methods. Were it found that the escape fractions of dwarf galaxies are, indeed, negligibly small, then new, more exotic sources of ionizing radiation (Population III stars, X-ray binaries, a new, previously unknown population of faint quasars, etc., but not the top-heavy IMF, since the conclusion presented in this Letter is independent of the stellar IMF and does not require any assumption about a particular shape for the IMF) would need to be invoked to explain the (relatively) early reionization of the universe at \( z \approx 6 \).

I thank Hsiao-Wen Chen, Andrej Kravtsov, Jordi Miralda, and the anonymous referee for valuable comments and corrections to the original manuscript. I am also grateful to Andrej Kravtsov for the permission to use his halo mass function code free of charge. This work was supported in part by the DOE, by the NSF grant AST-0507596, and by the Kavli Institute for Cosmological Physics at the University of Chicago.

REFERENCES

Bolton, J. S., & Haehnelt, M. G. 2007, MNRAS, 381, L35
Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2007, ApJ, 670, 928
Chen, H.-W., Prochaska, J. X., & Gnedin, N. Y. 2007, ApJ, 667, L125
Conroy, C., Wechsler, R. H., & Kravtsov, A. V. 2006, ApJ, 647, 201
Fan, X., et al. 2001, AJ, 122, 2833
———. 2006, AJ, 132, 117
Fernández-Soto, A., Lanzetta, K. M., & Chen, H.-W. 2003, MNRAS, 342, 1215
Giallongo, E., Cristiani, S., D’Odorico, S., & Fontana, A. 2002, ApJ, 568, L9
Gnedin, N. Y., Kravtsov, A. V., & Chen, H.-W. 2007, ApJ, submitted (arXiv: 0707.0879)
Hopkins, P. F., Richards, G. T., & Hernquist, L. 2007, ApJ, 654, 731
Kohler, K., Gnedin, N. Y., & Hamilton, A. J. S. 2007, ApJ, 657, 15
Leitherer, C., et al. 1999, ApJS, 123, 3
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Meiksin, A. 2005, MNRAS, 356, 596

Miralda-Escudé, J. 2003, ApJ, 597, 66
Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J.-G., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
Razoumov, A. O., & Sommer-Larsen, J. 2006, ApJ, 651, L89
———. 2007, ApJ, 668, 674
Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95
Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., & Erb, D. K. 2006, ApJ, 651, 688
Siana, B., et al. 2007, ApJ, 668, 62
Spergel, D. N., et al. 2003, ApJS, 148, 175
———. 2007, ApJS, 170, 377
Srbinovsky, J. A., & Wyithe, J. S. B. 2007, MNRAS, 374, 627
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1