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THE PHOTON UNDERPRODUCTION CRISIS

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ABSTRACT

We examine the statistics of the low-redshift Lyα forest from smoothed particle hydrodynamic simulations in light of recent improvements in the estimated evolution of the cosmic ultraviolet background (UVB) and recent observations from the Cosmic Origins Spectrograph (COS). We find that the value of the metagalactic photoionization rate ($\Gamma_{\rm HI}$) required by our simulations to match the observed properties of the low-redshift Lyα forest is a factor of five larger than the value predicted by state-of-the art models for the evolution of this quantity. This mismatch in $\Gamma_{\rm HI}$ results in the mean flux decrement of the Lyα forest being overpredicted by at least a factor of two (a 10σ discrepancy with observations) and a column density distribution of Lyα forest absorbers systematically and significantly elevated compared to observations over nearly two decades in column density. We examine potential resolutions to this mismatch and find that either conventional sources of ionizing photons (galaxies and quasars) must contribute considerably more than current observational estimates or our theoretical understanding of the low-redshift universe is in need of substantial revision.

Key words: cosmology: theory – diffuse radiation – intergalactic medium – large-scale structure of universe

1. INTRODUCTION

By virtue of its physical and chemical simplicity, the intergalactic medium (IGM) serves as an exquisite calorimeter, recording the instantaneous ionizing emissivity and heat produced by cosmic sources at each epoch. At $z < 6$ the IGM is highly ionized (Gunn & Peterson 1965), with a fluctuating residue of neutral hydrogen: the Lyα forest (Lynds 1971). After nearly two decades, the Lyα forest remains the most well-understood and robust prediction of cosmological hydrodynamic simulations (e.g., Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996; Miralda-Escudé et al. 1996; Rauch et al. 1997). This robustness arises because the Lyα forest is dominated by gas at moderate overdensity; gas that traces the dark matter (with only mild impact by pressure forces) and whose temperature is governed by the simple processes of photoionization heating and adiabatic cooling (e.g., Weinberg 1998; Peeples et al. 2010a). It is this simplicity that makes the calorimeter reliable: IGM models suggest the neutral fraction of gas at the cosmic mean density at $z \sim 3$ is $n_{\rm HI}/n_{\rm H} \sim 10^{-5.5}$ (e.g., Kollmeier et al. 2003), and this low neutral fraction must be maintained by the background of photoionizing radiation produced by quasars and star-forming galaxies (Miralda-Escude & Ostriker 1990; Haardt & Madau 1996), possibly augmented by other undiscovered sources.

Determining the intensity of the ultraviolet background (UVB)—specifically the hydrogen photoionization rate, $\Gamma_{\rm HI}$, is non-trivial. Because of its low surface brightness, the metagalactic UVB is not directly measured but is inferred through multiple independent channels, such as the quasar proximity effect (e.g., Bechtold et al. 1987; Scott et al. 2002) or the low surface brightness emission from the outskirts of galactic disks (e.g., Adams et al. 2011). The measurements are intrinsically difficult and subject to significant uncertainties and challenges (e.g., anisotropic QSO radiation, uncertain local gas densities). Alternatively, one can predict the intensity and spectrum of the UVB by synthesizing measurements of all possible sources of ionizing flux and the absorption and re-emission of UV radiation by the IGM and high column density absorbers (Haardt & Madau 1996, 2001, hereafter, HM01). While this procedure relies on a host of observational inputs, the most uncertain is the fraction $f_{\rm esc}$ of ionizing photons that escape from star-forming galaxies. Direct (and difficult) ionizing continuum measurements suggest that $f_{\rm esc} \sim 10\%$ at $z \sim 3$–4 (e.g., Shapley et al. 2006; Vanzella et al. 2010) and is substantially lower at $z < 1$ (e.g., Bridge et al. 2010; Barger et al. 2013).

Exploiting our theoretical understanding of the IGM provides a third avenue for probing $\Gamma_{\rm HI}$. By forcing a match between the (more easily observed and well understood) opacity of the Lyα forest and that from a theoretical IGM (typically taken directly from simulations) we have an independent determination that can be compared with both indirect measurements and the predicted UVB. There has historically been excellent agreement between the predicted UVB and the value inferred from the mean opacity (Davé & Tripp 2001). It was precisely the comparison between the predicted and observed forest opacity that provided strong arguments (now confirmed) for a "high" baryon density and low associated deuterium abundance (Rauch et al. 1997; Weinberg et al. 1997).

In this Letter, we demonstrate that this excellent agreement no longer holds at low redshift. Specifically, we will show a factor of five discrepancy between the $\Gamma_{\rm HI}$ predicted by the most

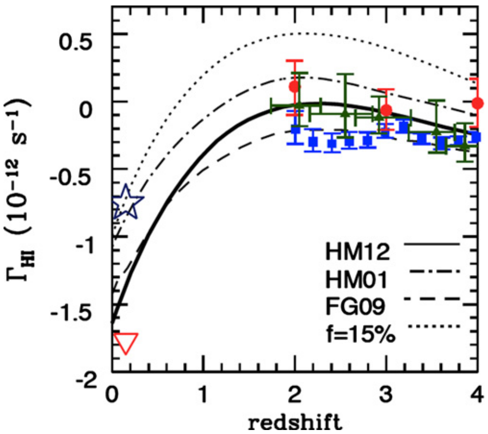

Figure 1. Photoionization rate as a function of redshift for the HM12, HM01 UVB (solid, dot-dashed) compared to observations at $z = 2$–4 (circles: Bolton & Haehnelt 2007, triangles: Becker et al. 2007, and squares: Faucher-Giguère et al. 2008) and the value we infer from our Lyα forest modeling at $z = 0.1$ (open star). The red triangle shows the low-redshift upper limit inferred by Adams et al. (2011) from non-detection of Hα emission in UGC 7321. The dashed line shows an alternative UVB model from Faucher-Giguère et al. (2009). The dotted line shows a model, discussed in Section 4.1, with a constant galaxy escape fraction $f_{\rm esc} = 15\%$.

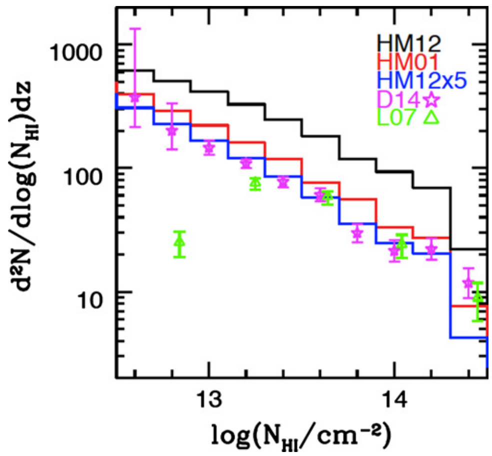

Figure 2. Column density distribution in the low-redshift IGM. Black (red) line shows the column density distribution determined from simulations adopting the HM12 (HM01) UVB estimates. The magenta data points shown are from COS observations from Danforth et al. (2014), while green symbols show the data from Lehner et al. (2007). The blue line shows a model in which HM12 is "boosted" by a constant factor of five (HM12 × 5).

sophisticated model of UVB evolution (Haardt & Madau 2012; hereafter HM12) and the value required to reproduce observed properties of the Lyα forest. We show in Figure 1 the predicted $\Gamma_{\rm HI}$ from HM12 (black solid line) compared to observational determinations. The dashed line shows an independent model of the UVB from Faucher-Giguère et al. (2009), which overall is quite similar to that of HM12. The large open star is the value reported here.

We take advantage of new measurements of the column density distribution (CDD) of the low-redshift Lyα forest from Cosmic Origins Spectrograph (COS) observations (Danforth et al. 2014) to determine $\Gamma_{\rm HI}$ by comparison with cosmological simulations of the IGM. We will further show that our conclusions would be very similar if we instead use the mean decrement as our observational measure.

After describing the cosmological simulation that we use (Section 2) and inferring the value of $\Gamma_{\rm HI}$ required to match the observed CDD (Section 3), we discuss (in Section 4) possible resolutions to the discrepancy between our inferred $\Gamma_{\rm HI}$ and the value predicted by HM12, the "photon underproduction crisis" (PUC) of our title. None of these resolutions alone appears entirely satisfactory. The most exciting possibility is that this discrepancy is probing exotic sources of ionizing photons or novel heating mechanisms in the diffuse IGM operating far above the usual theoretical expectations.

2. SIMULATIONS AND ARTIFICIAL SPECTRA

The simulations in this Letter are performed using a modified version of the Gadget2.0 smoothed particle hydrodynamics (SPH)+nbody code (Springel 2005; Oppenheimer & Davé 2008). We include radiative cooling from primordial composition gas and metals assuming ionization equilibrium. Our main simulation is performed within a box of $50\,h^{-1}$ Mpc on a side (co-moving) with 2×576^3 particles and LCDM cosmological parameters $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\Omega_b = 0.044$, $h = 0.70$. Our principal results are obtained from the $z = 0.1$ output of this simulation.

We stress at the outset that the results presented here should be robust to the adopted simulation code. At the physical scales and conditions of the Lyα forest, numerical issues of co-existing multi-phase media and under-or-over resolved hydrodynamic instabilities do not play a significant role. While our simulation adopts the momentum-driven wind ("vzw") formalism (described in detail by Oppenheimer & Davé 2008), and these winds can significantly heat the IGM close to galaxies, the overall Lyα forest properties of our simulations are largely insensitive to the adopted galactic wind prescription (e.g., Kollmeier et al. 2006; McDonald et al. 2006; Davé et al. 2010).

We extract 2500 spectra from our simulation boxes along a fixed grid using the Specexbin software package (Oppenheimer & Davé 2006). At each pixel position in the simulated sightline, the physical properties of the gas are computed (density, temperature, velocity, and metallicity) by considering the contribution of each overlapping SPH particle. The "physical space" spectra are converted to redshift space by incorporating the gas peculiar velocity, thermal motions, and the Hubble flow along the line of sight. The spectra are convolved with COS resolution and noise is added to produce signal-to-noise ratio (S/N) = 100. We use AutoVP (Davé et al. 1997) to analyze individual absorption systems in a way to mimic, as closely as possible, the corresponding observational procedure.

3. RESULTS

Figure 2 shows the CDD, defined here to be the mean number of absorbers per logarithmic interval of column density per unit redshift path length, for the simulated Lyα forest created with the HM12 and HM01 backgrounds. The COS CDD measurements from Danforth et al. (2014) are shown as magenta symbols. Earlier CDD measurements by (Lehner et al. 2007; green symbols) are in excellent agreement at column densities above 10^{13} cm^{-2} and are likely affected by incompleteness in the lowest column density bin. The simulated IGM is a thicker beast with the HM12 UVB determination, overpredicting the observed CDD by a factor of ≈3.3 over the column density range 10^{13}–10^{14} cm^{-2}. With the HM01 background, the simulated CDD is slightly but consistently above the COS measurements.

For a highly ionized system in photoionization equilibrium, the neutral column density is inversely proportional to the photoionization rate, $N_{\rm HI} \propto 1/\Gamma_{\rm HI}$. The slope of the simulated and observed CDDs in Figure 2 is approximately $N_{\mathrm{HI}}^{-0.75}$, so reducing the amplitude of the CDD by a factor of 3.3 requires lowering the column densities of individual systems by a factor of $3.3^{1/0.75} \approx 5$. The blue histogram in Figure 2 shows the CDD computed from the simulation with the HM12 UVB increased in amplitude by a factor of five, and the agreement with the Danforth et al. (2014) data is now very good. There is some tension in the highest column density bin, where line saturation effects are beginning to become important and details of fitting algorithms, observational noise, and spectral resolution may play a larger role.

The mean flux decrement for the simulated spectra is $\langle D \rangle =$ 0.05, 0.024, and 0.018 for the HM12, HM01, and boosted HM12 backgrounds, respectively. These can be compared to the value of $\langle D \rangle = 0.020 \pm 0.003$ found by Kirkman et al. (2007) from observed Lyα forest spectra at low redshift. The mean decrement results lead to exactly the same conclusion as the CDD analysis, requiring a factor of ≈5 boost in the amplitude of Γ_{HI} relative to the HM12 prediction. The CDD comparison has the virtue of focusing on systems that are the most physically simple[12] (i.e., moderate overdensity of ≈5–20 at $z = 0$) and the most straightforward to measure observationally, but the similarity of the results demonstrates the robustness of the conclusion.

4. DISCUSSION

The large mismatch between the low-redshift photoionization rate predicted by HM12 and inferred from matching the observed CDD challenges[13] our current understanding of the sources of the UVB, the physical state of the IGM, or both. We now discuss a number of possible resolutions to this discrepancy.

4.1. Galaxy Escape Fraction

From the point of view of the low-redshift Lyα forest, the most important change between HM01 and HM12 is a different model for the escape fraction of ionizing photons from galaxies, f_{esc}.[14] To simultaneously match the high escape fractions required at $z > 5$ to explain reionization and the much lower f_{esc} inferred from Lyman continuum observations of galaxies at $z \sim 3$ (typically a few percent, e.g., Shapley et al. 2006; Boutsia et al. 2011), HM12 adopt an evolving mean escape fraction $f_{\mathrm{esc}} = 1.8 \times 10^{-4}(1 + z)^{3.4}$. As a result, the contribution of galaxies to Γ_{HI} is modest at $z = 3$ and negligible at $z = 0$, while in HM01 the galaxy and quasar contributions are comparable at both redshifts. From calculations with HM12's CUBA code, we find that producing our inferred low-redshift Γ_{HI} while keeping other aspects of the HM12 model fixed requires an escape fraction $f_{\mathrm{esc}} \approx 15\%$, as shown by the dotted curve in Figure 1. This simple model significantly overshoots (factor ∼3) the background at $z = 2$–4. Therefore, resolving the PUC with ionizing radiation from galaxies would require f_{esc} to evolve non-monotonically between $z = 6$ and $z = 0$. Most seriously, the required f_{esc} is incompatible with most direct searches for Lyman continuum radiation from star-forming galaxies at $z = 0$–1.5 (e.g., Bridge et al. 2010; Barger et al. 2013).

[12] While the mean decrement is dominated by low column density Lyα forest systems, there is a non-negligible contribution from high column density systems associated with galaxies that can, in principle, complicate both the observational and theoretical analysis.

[13] Significantly. Hence "Photon Underproduction *Crisis*."

[14] Defined here to represent the average fraction of 1–4 ryd photons that escape their host galaxies.

4.2. Quasar Emissivity

The low-redshift quasar emissivity in HM12 is about a factor of two below that in HM01, a consequence of changing the adopted mean quasar spectral energy distribution (SED) and the adopted luminosity function (primarily the latter). The quasar SED in HM12 is harder than in HM01, bringing it into significantly better (although not perfect) agreement with the most recent measurements of the SED shape (Shull et al. 2012). Recent estimates of the evolving quasar luminosity function also imply a somewhat reduced emissivity at low redshift (e.g., Hopkins et al. 2007; Cowie et al. 2009). At the factor of two level the estimated contribution of quasars to the low-redshift UVB has remained stable for nearly two decades; for example, Shull et al. (1999) infer $\Gamma_{\mathrm{HI}}(z = 0) = 3.2 \pm 1.2 \times 10^{-14}\,\mathrm{s}^{-1}$, which is compatible with the HM12 value of $2.3 \times 10^{-14}\,\mathrm{s}^{-1}$. It therefore seems unlikely that this contribution could be increased by a factor of five relative to the HM12 value, or even by the factor of two that would get back to HM01's estimate of the quasar emissivity. Corrections of this magnitude would require a dominant contribution from systems that have largely escaped the existing census of active galactic nuclei (AGNs). In addition to being heretofore invisible, these systems would necessarily have substantially different SEDs from standard AGN so that they could dominate the UVB without overproducing the directly observed X-ray background.

4.3. Mean Free Path

At high redshift, the intensity of the UVB is controlled in part by the mean free path of ionizing photons, which sets the horizon over which a given source's Lyman continuum radiation can influence the IGM. HM01 and HM12 compute the radiative transfer of UVB photons using observational estimates of the frequency of high column density Lyα absorbers ($N_{\mathrm{HI}} \gtrsim 10^{15}\,\mathrm{cm}^{-2}$). While these estimates remain somewhat uncertain, the mean free path becomes large at $z < 1$ in any case, so that the horizon is set by cosmological redshifting rather than by absorption. As a test, we have run CUBA in a case where we double the mean free path at $z < 1$, a change already inconsistent with observations (Stengler-Larrea et al. 1995; Ribaudo et al. 2011), and find that $\Gamma_{\mathrm{HI}}(z = 0)$ only increases by a factor of 1.4.

4.4. Extra Heating of the IGM

It is possible that there is a source of IGM heating that is not accounted for by our simulations. In conventional models, the temperature–density relation of the diffuse IGM is determined by the balance between heating by photoionization and adiabatic cooling by the expansion of the universe (e.g., Katz et al. 1996; Hui & Gnedin 1997). For temperatures $T \lesssim 2 \times 10^5$ K, the hydrogen recombination coefficient scales as $T^{-0.7}$, so a hotter IGM produces a thinner Lyα forest. The H I column density of a given system scales as $T^{-0.7}\Gamma_{\mathrm{HI}}{}^{-1}$, so a factor of five increase in Γ_{HI} achieves the same effect as a factor of $5^{1/0.7} \sim 10$ increase in temperature.

To examine the amount of heating required to resolve this discrepancy, we have carried out the simple experiment of boosting the temperature of all SPH particles in the simulation by a factor of four before extracting Lyα forest spectra with the HM12 UVB, and we find that the resulting CDD is similar to but slightly above that of the HM01 model shown in Figure 2, as expected by comparing $4^{0.7} = 2.6$ to the factor of 3.7 difference in Γ_{HI} between HM01 and HM12.

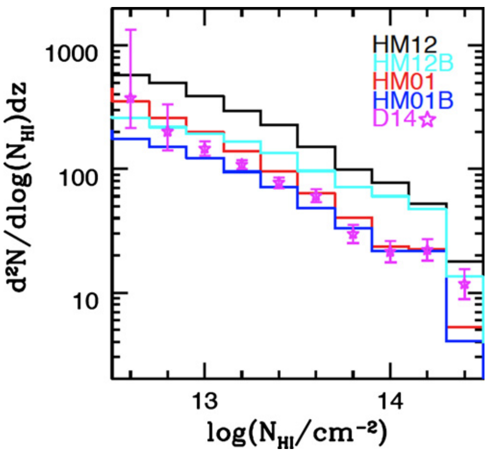

Figure 3. Effect of blazars on the low-redshift Lyα forest statistics. Black, cyan, red, and blue lines correspond to simulations performed with the HM12 background, HM12 background plus blazars, HM01 background, and HM01 background plus blazars, respectively.

A harder ionizing background spectrum leads to a hotter IGM temperature because the average residual energies of photoelectrons are higher. However, producing even a factor of four increase in temperature would require an implausibly hard UVB spectral shape, so the extra heating solution would require some mechanism other than photoionization. Broderick et al. (2012) have proposed one such mechanism, powered by TeV gamma-ray emission from blazars. These high energy gamma rays annihilate and pair-produce through interactions with extragalactic background photons. In principle, this process can drive a plasma instability, which locally dissipates the (high) energy of the produced pair, thereby heating the low-density IGM. This heating results in an inverted temperature–density relation in the forest because it deposits more energy per particle (Puchwein et al. 2012).

To investigate the potential impact of blazar heating, we have performed a suite of simulations implementing the "intermediate" prescription for blazar heating proposed by Puchwein et al. (2012), and confirmed that we reproduce their results for the T–ρ relation at $z = 3$ and $z = 0$.[15] This simulation was performed at slightly lower resolution, with 2×384^3 particles in a $48\,h^{-1}$ Mpc box, and we ran a matched simulation without blazar heating for comparison. The blazar heating has the anticipated effect of thinning out the Lyα forest at low redshift for both the HM12 and HM01 UVB models as shown in Figure 3. The shallower CDD for the blazar simulation is a result of the inverted ρ–T relation, which reduces the neutral fraction in the lower density gas responsible for lower column density absorbers. This highlights the potential to use the low-redshift Lyα forest CDD to probe the impact of blazar contributions to the heating of the low-density IGM. However, blazar heating is clearly insufficient to reconcile the HM12 background with the observed CDD. If we instead apply the HM01 background to the blazar simulation we get reasonably good agreement with the Danforth et al. (2014) CDD, but most of this improvement comes from the larger $\Gamma_{\rm HI}$ of HM01.

4.5. Density Structure of the IGM

It is possible that our cosmological simulations are predicting the wrong density structure of the diffuse IGM owing to either cosmological or numerical inaccuracies. We believe both of these are unlikely. At our simulation resolution, the properties of the forest are well-converged and largely insensitive to, e.g., wind model, feedback prescriptions, spectral resolution, and noise characteristics (Davé et al. 2010; Peeples et al. 2010b). A cosmological solution would require making the low-redshift IGM much smoother than LCDM simulations predict–shifting absorption systems systematically to lower columns or erasing them entirely. It is possible that cosmological models including warm dark matter or a small scale cutoff in the primordial power spectrum would go in this direction, but we are skeptical that any such change could resolve the PUC while maintaining a good match to the observed Lyα forest. With our preferred UVB intensity, on the other hand, LCDM simulations match observed Lyα forest and metal-line absorption statistics over a wide range of redshifts.

4.6. New Sources of Ionizing Photons

The most exciting interpretation of the PUC is that it has revealed the presence of previously unrecognized (and dominant) sources of ionizing photons in the low-redshift universe. A population of low-luminosity or hidden AGN could be such a source, though this would require a major revision to our understanding of the AGN luminosity function. Lyman continuum searches have mostly focused on rapidly star-forming galaxies, and it is possible that a different population, such as early-type galaxies producing UV radiation from core helium burning or post-asymptotic giant branch stars, dominates the production of ionizing photons. More exotically, the "missing" photons could be coming from decaying or annihilating dark matter particles in the dense cores of halos and subhalos. Producing the implied energy density of the low-redshift UVB would only require the decay of $\sim 10^{-8}$ of the dark matter density over a Hubble time, so this solution would not significantly alter cosmological parameters, but it would have profound implications for dark matter properties.

Further studies of Hα emission from nearby galaxies are an important area for future work, as confirmation of the Adams et al. (2011) limit on $\Gamma_{\rm HI}$ would rule out all solutions involving additional ionization, including those in Sections 4.1–4.3.

5. CONCLUSIONS

The factor of five discrepancy between the value of $\Gamma_{\rm HI}$ required to match cosmological models of the $z = 0$ IGM to the observed mean decrement and CDD and that predicted by state-of-the-art models for the evolution of the extragalactic UVB (HM12) highlights a significant gap in our current understanding of the sources of the UV background or the structure of the IGM, or both. We have discussed a number of possible resolutions, no one of which appears satisfactory. The least radical solution is to increase the mean $f_{\rm esc}$ at low redshift such that galaxies dominate the emissivity and simultaneously boost the quasar emissivity, though both of these changes oppose our current understanding of these sources. For the undaunted, extra photons from decaying dark matter or a drastic change to the physical structure of the IGM as predicted by LCDM may also be the resolution to the PUC.

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[15] The temperature at $\bar{\rho} = 1$ is $\approx 10^{4.4}$ K at $z = 0$ in this model compared with $\approx 10^{3.6}$ K for fiducial; the T–ρ logarithmic slope is -0.95 compared to 0.55.

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