REIONIZATION, SLOAN, AND WMAP: IS THE PICTURE CONSISTENT?

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ABSTRACT

I show that advanced simulations of cosmological reionization are able to fit the observed data on the mean transmitted flux in the hydrogen Lyα line at z ~ 6. At the same time, a posteriori models can be constructed that also produce a large value (20%) for the Thompson scattering optical depth, consistent with the Wilkinson Microwave Anisotropy Probe (WMAP) measurements. Thus, it appears that a consistent picture emerges in which early reionization (as suggested by WMAP) is complete by z ~ 6, in accord with the Sloan data.

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

1. INTRODUCTION

Are we knocking at the door of reionization? At least, it seems so, as the Sloan quasar survey continues to find ever more distant quasars (Becker et al. 2001; Fan et al. 2002, 2003; White et al. 2003). In fact, the highest redshift quasars show essentially no transmitted flux just blueward of the quasar Hα region, which has been interpreted as evidence that that reionization took place at a redshift z ~ 6 (Becker et al. 2001; White et al. 2003; a similar claim has also been made by Djorgovski et al. 2001 based on an extrapolation from lower redshift observations).

However, one should be cautious before drawing such a conclusion. Indeed, the observed decrease in the mean transmitted flux at z ~ 6 might simply indicate a decrease in the mean ionizing intensity rather than a real reionization of the universe. After all, a neutral fraction of only 2 x 10^{-4} is sufficient to absorb effectively all Lyα radiation at z = 6 even in gas that is underdense by a factor of 10. Thus, without an understanding of the evolution of the universe around the reionization epoch, the Lyα absorption data cannot be used to constrain the epoch of reionization (unless damping wings are observed in the absorption profiles; Miralda-Escudé 1998).

Fortunately, our theoretical understanding of the process of reionization, in part based on numerical simulations, is solid enough that the evolution of the ionizing intensity at these redshifts can be predicted with a reasonable confidence level. Combining simulations with the observational data indeed allows one to come up with a consistent picture of the process of cosmological reionization.

2. SIMULATIONS

Four sets of simulations have been performed with the SLH code and are similar to the simulations reported in Gnedin (2000). The main difference from previous simulations is that a newly developed and highly accurate optically thin variable Eddington tensor (OTVET) approximation for modeling radiative transfer (Gnedin & Abel 2001) is used instead of a crude local optical depth approximation. The new simulations therefore should be sufficiently accurate (subject to the usual limitations of numerical convergence and phenomenological description of star formation) to be used meaningfully in comparing with the observational data. In particular, my fiducial model uses the cosmological parameters as determined by the WMAP satellite (Spergel et al. 2003).

Parameters of the four sets are given in Table 1. All simulations included 128^3 dark matter particles, an equal number of baryonic cells on a quasi-Lagrangian moving mesh, and about 3 million stellar particles that formed continuously during the simulation. The nominal spatial resolution of simulations with a box size of 4 h^{-1} Mpc was fixed at 1 h^{-1} comoving kpc, with the real resolution being a factor of 2 worse. Simulations with a box size of 8 h^{-1} Mpc had a 2 times worse spatial resolution.

In all cases a flat cosmology was assumed, with \Omega_{\Lambda,0} = 1 - \Omega_{m,0}, and normalization of the primordial fluctuations was determined either from the WMAP data (Spergel et al. 2003) for sets A4 and A8 or from the COBE data (White & Bunn 1995). Note that a small change in the slope of the primordial power-law spectrum n has a significant effect on the amount of the small-scale power because of the large leverage arm from cosmic microwave background scales to the tens of kpc scales that are important for reionization.

Star formation is incorporated into the simulations using a phenomenological Schmidt law, which introduces two free parameters: the star formation efficiency \epsilon_{\rm SF} (as defined by eq. [1] of Gnedin 2000) and the ionizing radiation efficiency \epsilon_{\rm UV} (defined as the energy in ionizing photons per unit of the rest energy of stellar particles). The star formation efficiency \epsilon_{\rm SF} is chosen so as to normalize the global star formation rate in the simulation at z = 4 to the observed value from Steidel et al. (1999), whereas the ultraviolet radiation efficiency \epsilon_{\rm UV} is only weakly constrained by the (highly uncertain) mean photoionization rate at z ~ 4. The redshift of reionization strongly depends on \epsilon_{\rm UV}; however, since the simulations are quite expensive, it is not possible to cover a large range of \epsilon_{\rm UV} in a given set. Typically, only two or three simulations per set have been performed, and the results are then interpolated between the simulations. This procedure is fully described in § 4.

3. A “REDSHIFT OF REIONIZATION”: WHAT IS IT?

Reionization is a process, not an event. In fact, the whole process of reionization is quite extended (\Delta z \sim 5-10) and can be generically separated into three stages: (1) the pre-overlap
stage, in which individual H ii regions around the sources of ionization expand and merge into the low-density IGM, (2) the overlap stage, in which all individual H ii regions overlap and last the remnants of the neutral low-density gas quickly disappear, and (3) the post-overlap stage, in which the remaining high-density gas is being ionized from the outside, until neutral gas remains only in some of the highest density regions, which would be identified as Lyman-limit systems in the absorption spectra of distant quasars.

One can think of reionization as complete when the mean free path to the ionizing radiation is fully determined by (relatively) slowly evolving Lyman-limit systems (Miralda-Escude 2003a). It is, however, tempting to try to assign a value for the “redshift of reionization.” Such a value, in order not to be completely arbitrary, must be related to the physics of the reionization process. For example, it seems natural to identify the moment of reionization with the overlap stage, but even it takes place over a sizable redshift interval $z_{\text{rei}}$ (Gnedin 2000), so we need a better definition if we are to assign a value to the redshift of reionization.

Fortunately, such a definition exists. Figure 1 shows the mean free path to ionizing radiation and its time derivative as a function of redshift for simulation A4 from Table 1. The mean neutral fraction has a well-defined peak in the middle of the overlap stage, which is a natural moment to identify with the redshift of reionization $z_{\text{rei}}$.

However, this definition is not entirely practical, since the time derivative of the mean free path cannot be observed directly. Instead, a more easily observable quantity is the mean neutral fraction. Figure 2 shows the mean mass- and volume-weighted neutral hydrogen fractions for the fiducial simulation. The moment of reionization closely corresponds to the time when the mean mass- and volume-weighted neutral fractions reach values of $10^{-2}$ and $10^{-3}$, respectively.

The latter definition is more practical, but it is subject to an important clause: while the volume-weighted neutral fraction is reliably computed in the simulation, the mass-weighted one depends on the numerical resolution. In particular, the simulations presented in this paper do not resolve the damped Ly$\alpha$ systems, so the above-quoted value of 1% for the mass-weighted neutral fraction does not include the neutral gas locked in the damped Ly$\alpha$ systems. In this respect, the volume-weighted number is more robust and should be used as a main definition of the redshift of reionization.

4. RESULTS

4.1. Fitting the Mean Transmitted Flux Data

Figure 3 shows the mean transmitted flux as a function of redshift for the three simulations with different values of the $\epsilon_{\text{UV}}$ parameter from set B4. The observational data shown with open circles were obtained from White et al. (2003) by averaging the mean transmitted flux at a given redshift interval. The vertical error bars are errors of the mean (not mean errors!). The horizontal error bars are simply the width of the redshift interval over which the mean transmitted flux is computed. The last data point (without the vertical error bar) is likely to be contaminated by a foreground galaxy and is not included in this analysis. The filled squares show the data from Songaila (2004). In the latter case I do not show the error bars for clarity, but they are comparable to those of White et al. (2003).

The two gray lines are the solid black line simply shifted horizontally. As one can see, the change in the $\epsilon_{\text{UV}}$ parameter simply translates into the shift in redshift. This is not

![FIG. 1.—Mean free path to ionizing radiation (bottom) and its time derivative (top) as a function of redshift for simulation A4 from Table 1.](image1)

![FIG. 2.—Mass-weighted (solid line) and volume-weighted (dashed line) neutral hydrogen fractions as a function of redshift for simulation A4 from Table 1. Note that the peak in the time derivative of the mean free path (vertical dashed line) closely corresponds to the moment when the mean mass- and volume-weighted neutral fractions reach values of $10^{-2}$ and $10^{-3}$, respectively.](image2)
surprising given that in the cold dark matter model clustering proceeds hierarchically, in a quasi--self-similar manner. In other words, one would expect that the dependence of the mean transmitted flux on the emissivity parameter $\epsilon_{\text{UV}}$ and redshift $z$ enters, to first order, only as

$$\langle F \rangle(z) = (1 + z)^{\beta} g [\epsilon_{\text{UV}} (1 + z)^{-\alpha}], \quad (1)$$

where $g$ is a function of one argument and $\alpha$ and $\beta$ depend on the slope of the primordial power spectrum at the scale of interest and may also depend on the details of the temperature-density relation. But because I am only concerned with a narrow redshift range around $z = 6$ (for example, $z = 5.8 - 6.5$ in Fig. 3), $\alpha$ and $\beta$ from equation (1) can be considered constant in the first approximation. Figure 3 indicates that for the range of redshifts considered, $\beta$ is small, less than about 0.5 in the absolute value. The specific reason for such a small value is not entirely clear and may be a simple coincidence: if $\epsilon_{\text{UV}}$ is reduced, the amount of ionizing radiation in the post-overlap stage is also reduced, but at the same time the post-overlap stage is delayed to lower redshifts when densities are lower. The two effects appear to approximately cancel each other, leading to a small value of $\beta$.

The main result of Figure 3 is that a change in the emissivity parameter $\epsilon_{\text{UV}}$ by a factor of $f$ simply translates into a rescale of $(1 + z)$ redshift by a factor $f^{1/\alpha}$. Note that such rescaling does not affect the vertical amplitude of the mean transmitted flux curve. As is well known, the mean absorption after the post-overlap stage is dominated by the Lyman-limit systems (Miralda-Escude 2003b). Thus, in order to reproduce the observed run of the mean transmitted flux with redshift, a simulation must have (1) the right value for the emissivity parameter $\epsilon_{\text{UV}}$ (i.e., the right value for the recombination stage) to reproduce the drop-off at $z \sim 6$, and (2) the correct abundance of the Lyman-limit systems. The latter is crucially dependent on the abundance of low-mass virialized objects and is not completely controlled by the parameter $\epsilon_{\text{UV}}$ but also depends on the mass function of virialized objects, i.e., on cosmological parameters. Therefore, if a simulation has wrong values of cosmological parameters, it might not be able to reproduce the amplitude of the mean transmitted flux as a function of redshift for any value of the single free parameter $\epsilon_{\text{UV}}$.

This is illustrated in Figure 4, which shows the results from three simulation sets (A4, B4, and C4), each rescaled for the best value of the emissivity parameter $\epsilon_{\text{UV}}$ (the simulation set C4 has not been continued beyond $z = 5.5$). As one can see, not all of the simulation sets are able to reproduce the amplitude of the mean transmitted flux curve. For example, set C4 predicts a factor of 10 more absorption: in that cosmological model ($\Omega_m = 0.35$, $\sigma_8 = 0.97$), the amount of small-scale power is significantly larger than, say, in the WMAP model, and the mean distance between Lyman-limit systems is a factor of 10 less than the observed value. Sets A4 and B4, on the other hand, provide a reasonable, although not perfect, fit to the data. In fact, it appears that set A4 (the WMAP model) fits the data best for $z > 5.2$ but goes somewhat below the data points at lower redshifts. This is expected, since because of the limited size of the computational box, simulations should underpredict the abundance of ionizing sources at lower redshifts. Simulation set B4 has a somewhat higher mean transmitted flux, although it is marginally consistent with the data given the cosmic variance.

There is no easy way to reconcile model C4 (and, perhaps, model B4) with the data. The abundance of the Lyman-limit systems depends not only on $\epsilon_{\text{UV}}$ but also on the cosmological model, and as long as $\epsilon_{\text{UV}}$ and the cosmological parameters are specified, there is no free parameter left to adjust this abundance. The only way to make, say, model B4 fit the data better would be to include additional Lyman-limit absorption a posteriori, by hand—for example, by postulating an entirely different class of objects that contribute to the mean free path but do not form within the hierarchical clustering framework. For model C4, however, one would have to postulate that some of the Lyman-limit systems that form in the simulation do not form in reality.

**4.2. Measuring the Redshift of Reionization**

Using the fact that the WMAP model fits the observed data, one can determine how much the redshift of reionization can be shifted while still preserving the acceptable fit to the data. Figure 5 shows the range of values for the redshift of reionization for models A4 and B4 (although the latter is
admittedly a worse fit to the data) obtained by adding linearly two different components: (1) an average observational error bar in the $z$-direction (0.085) and (2) the average uncertainty to the best-fit value of $z_{\text{rei}}$ for the fiducial model. With these three uncertainties included, a measurement of the redshift of reionization can be made:

$$z_{\text{rei}} = 6.1 \pm 0.3 \quad (95\% \text{ CL}).$$

If other cosmological models are also considered (for example, model B4), then an additional “systematic” uncertainty is introduced because of small differences in the redshifts of reionization of different cosmological models. This uncertainty, however, is rather small, as can be seen from Figure 5, and is ignored here.

### 4.3. Sanity Checks

Before I can proceed further, several sanity tests must be completed. The first two are shown in Figure 6. The light gray line is again the best-fit fiducial *WMAP* model, with error bars showing the rms fluctuation in the mean transmitted flux (error of the mean); this is consistent with (although slightly smaller than) the observed values. This is not surprising, since a finite (and relatively small) size of the computational volume will lead to an underestimate of the cosmic variance.

How significant is this underestimate? In order to reduce the cosmic variance at the box size scale, the specific realizations of initial conditions are selected to reproduce the correct power spectrum of initial perturbations on the fundamental mode (Gnedin & Hamilton 2002), which mitigates the uncertainty due to cosmic variance by about a factor of 10 or more. To demonstrate that numerical convergence is achieved for the mean transmitted flux and that cosmic variance does not affect my results, I show with the dark gray line in Figure 6 the best-fit simulation from the A8 set (the same cosmological model, a 2 times larger box). The fact that the two simulations with the two box sizes are sufficiently close argues for the numerical convergence of the simulation result, although admittedly this is not a 100% rigorous test (three different resolutions would be required for a complete test, but this is currently beyond existing computer capabilities).

The recent results from the *WMAP* measurement of the cross-correlation between the temperature and polarization anisotropies of the cosmic microwave background indicate the large value of the Compton optical depth $\tau = 0.12 \pm 0.06$ (Kogut et al. 2003; Tegmark et al. 2004). Does this observation rule out reionization at $z \sim 6$? Figure 7 shows the ionization histories for the fiducial model (black line) and three arbitrary ionization histories (gray lines) with $\tau = 0.2$. All four models have the identical reionization redshift of $z_{\text{rei}} = 6.1$. Thus, the *WMAP* measurement by itself neither constrains the redshift of reionization nor contradicts the Sloan data, but rather indicates that the early ionization history might have been quite complex.

### 5. CONCLUSIONS

I have shown that advanced self-consistent cosmological simulations with radiative transfer are able to reproduce the
observed data on the evolution of the mean transmitted flux from the Sloan survey when the values of the cosmological parameters that best fit the WMAP data are adopted for the underlying cosmology. Thus, a consistent picture is emerging in which the universe reionizes at \(6.1 \pm 0.3\) after possibly a prolonged period of partial reionization.

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