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STATISTICS OF NEUTRAL REGIONS DURING HYDROGEN REIONIZATION

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ABSTRACT

We present predictions for two statistical measures of the hydrogen reionization process at high redshift. The first statistic is the number of neutral segments identified in spectra of high-redshift QSOs as a function of their length. The second is the cross-correlation of neutral regions with possible sources of ionizing radiation. These independent probes are sensitive to the topology of the ionized regions. If reionization proceeded from high- to low-density regions, then the cross-correlation will be negative, while if voids were ionized first we expect a positive correlation and a relatively small number of long neutral segments. We test the sensitivity of these statistics for reionization by stars in high-redshift galaxies. The flux of ionizing radiation emitted from stars is estimated by identifying galaxies in an N-body simulation using a semianalytic galaxy formation model. The spatial distribution of ionized gas is traced in various models for the propagation of the ionization fronts. A model with ionization proceeding from high- to low-density regions is consistent with the observations of Becker et al., while models in which ionization begins in the lowest density regions appear to be inconsistent with the present data. Further data are required to confirm this result.

Subject headings: cosmology: observations — cosmology: theory — dark matter — intergalactic medium — large-scale structure of universe — quasars: absorption lines

1. INTRODUCTION

Early hydrogen reionization is a particularly interesting process in the high-redshift universe and is inevitably linked to the appearance of the first star-forming objects, at least those that served as sources of the ionizing radiation. If it occurred early enough, reionization imprints distinct features in maps of the cosmic microwave background (CMB) on arcminute angular scales (Vishniac 1987; Bruscoli et al. 2000; Benson et al. 2001, hereafter BNSL). Several aspects of hydrogen reionization remain uncertain despite the rapidly accumulating data on the high-redshift universe. For example, it is unclear what objects produce most of the ionizing radiation, although high-redshift galaxies are very strong candidates (Couchman & Rees 1986; Haiman & Loeb 1997; Ciardi et al. 2000). It is also unclear how the ionized regions develop in space (Miralda-Escudé, Haehnelt, & Rees 2000). The ionizing sources are likely to lie in high-density regions, but those regions do not necessarily ionize first; the ionizing photons may tunnel into less dense regions and ionize those first. Furthermore, the duration of reionization is unknown, and only a lower limit on the redshift marking the end of that epoch exists (Becker et al. 2001; Gunn & Peterson 1965).

In previous papers (BNSL; Liu et al. 2001), we examined how the CMB is affected by the reionization process and how future CMB maps can be used to extract information on that process. However, hydrogen reionization is currently best probed by spectra of high-redshift QSOs. Unlike maps of the CMB that are sensitive to line-of-sight integrals over the density and velocity of ionized gas, QSO spectra contain direct information on the local distribution of neutral hydrogen.

Recently, Becker et al. (2001) analyzed spectra of a sample of QSOs with redshifts between \( z = 5.82 \) and \( z = 6.28 \). In the spectrum of their highest redshift QSO \( z = 6.28 \), the transmitted flux in the Ly\( \alpha \) and Ly\( \beta \) forest in the redshift stretch \( 5.95 < z < 6.16 \) is consistent with zero, with a lower limit of 20 on the Ly\( \alpha \) optical depth. This long stretch in redshift corresponds to a comoving distance of 60 \( h^{-1} \) Mpc in a universe with a cosmological constant of \( \Omega_m = 0.7 \) and matter density of \( \Omega_0 = 0.3 \). Becker et al. (2001) suggest that this long neutral region is a detection of the end of the hydrogen reionization era. To increase the signal-to-noise ratio, Becker et al. binned their spectra in 4 \( \AA \) pixels. This prevented them from detecting small-scale dark windows that are likely to appear in the spectra as leftovers from the reionization epoch. A high-resolution spectrum for one of the quasars observed by Becker et al. was obtained by Djorgovski et al. (2001). The spectrum of this quasar \( z = 5.73 \) was thoroughly analyzed by Djorgovski et al. (2001) and was found to contain several small dark windows, signifying the detection of the trailing edge of the reionization epoch.

Motivated by the results of Becker et al. (2001) and Djorgovski et al. (2001), we examine here how the key ingredients in the reionization process can be probed by QSO spectra and future high-redshift galaxy surveys. Using the methodology of BNSL, we obtain predictions for two statistics. The first is the expected number of neutral segments longer than a given length, and the second is the cross-correlation function between the galaxies and neutral regions.

2. MODELING THE DEVELOPMENT OF IONIZED REGIONS

BNSL employed a semianalytical model for galaxy formation in a high-resolution \( N \)-body simulation of dark matter to estimate the amount of ionizing radiation produced by stars in high-redshift galaxies. Here we follow a similar procedure using the latest version of the GAlFORM galaxy formation model (Cole et al. 2000) and the same \( \Lambda \)CDM simulation as BNSL (cf. Jenkins et al. 1998). This simulation has \( \Omega_m = 0.3 \), \( \Omega_\Lambda = 0.7 \), and a mean density contrast of \( \delta_m = 200 \) at the virialization of halos. The semianalytical model uses the GABRIELLE galaxy formation model (Benson et al. 2001) to predict the number density of galaxies as a function of redshift and halo mass. The galaxy mass function is then used to populate halos with galaxies according to their abundance. The galaxy and halo properties are then evolved in time using a set of equations that describe the evolution of the galaxy population as a function of cosmic time. The galaxy model includes star formation, feedback from supernovae, and dark matter halos, as well as the effects of dwarf galaxies and the evolution of the intergalactic medium. The resulting galaxy population is then used to predict the number density of galaxies as a function of redshift and halo mass.

The semianalytical model is used to predict the number density of galaxies as a function of redshift and halo mass. The galaxy mass function is then used to populate halos with galaxies according to their abundance. The galaxy and halo properties are then evolved in time using a set of equations that describe the evolution of the galaxy population as a function of cosmic time. The galaxy model includes star formation, feedback from supernovae, and dark matter halos, as well as the effects of dwarf galaxies and the evolution of the intergalactic medium. The resulting galaxy population is then used to predict the number density of galaxies as a function of redshift and halo mass.
to produce the observed abundance of rich clusters at
the large scale. Here we adopt the simplest model, in which
is constant for all
amount of ionizing radiation increases significantly between
\( z \approx 0 \) (see BSNL for details).

Assuming a value\(^7\) for \( f_{\text{esc}} \), BNSL used the following models
to follow the propagation of ionized regions in the simulation
(see BSNL for details).

**Model A (growing front model).**—We ionize a spherical vol-
ume around each source (halo) with a radius equal to the in-
ionization front radius for that halo assuming a large-scale uniform
distribution of neutral hydrogen. Since the neutral hydrogen in
the simulation is not uniformly distributed, and also because
some spheres will overlap, the ionized volume will not contain
the correct total mass of hydrogen. We therefore scale the radius
of each sphere by a constant factor and keep repeating the
procedure until the correct total mass has been ionized.

**Model B (high-density model).**—We simply rank the cells in
the simulation volume by their density. We then completely
ionize the gas in the densest cell. If this has not ionized enough
hydrogen, we ionize the second densest cell. This process is
repeated until the correct total mass of hydrogen has been
ionized.

**Model C (low-density model).**—Same as model B, but we
begin by ionizing the least dense cell, and work our way up
to cells of greater and greater density (Miralda-Escudé et al.
2000).

**Model D (random spheres model).**—Same as model A, but the
spheres are placed in the simulation entirely at random
rather than on the dark matter halos.

**Model E (boundary model).**—We ionize a spherical region
around each halo with a radius equal to the ionization front
radius for that halo. This may ionize too much or not enough
neutral hydrogen depending on the density of gas around each
source. We therefore begin adding or removing cells at random
from the boundaries of the already ionized regions until the
required mass is ionized.

Models A, B, and E all are associated with ionization starting
in the highest density regions. The differences among them will
serve as an assessment of the sensitivity of the proposed sta-
tistics. Model C is motivated by Miralda-Escudé et al. (2000).
In the random sphere model (D), the ionized bubbles are un-
correlated and serve to test the effect of the correlation. Model
D also approximates a situation in which in some regions in
space ionization proceeds from high densities while in others
from the voids.

Guided by the observations of Becker et al. (2001), we will
compute the number of neutral segments and the cross-corre-
lations at three redshifts, \( z = 6.67, 6.22, \) and 5.80. Table 1 lists
the volume filling factors (ratio of volume of ionized regions to
total volume of the simulation box) in each of our five models
for \( f_{\text{esc}} = 0.01 \) (col. [3] in Table 1) and \( f_{\text{esc}} = 0.05 \) (col. [4]).
We will see later that the results of Becker et al. imply that the
amount of ionizing radiation increases significantly between
\( z \approx 6.2 \) and 5.8. Therefore, we also show results for a variable
escape fraction, \( f_{\text{esc}} \) (col. [5]), which equals 0.01 before \( z = 6.22 \) and increases linearly with time to 0.1 at \( z = 5.8 \). As ex-
pected, model C (low-density model) has the highest filling factor
for a given \( f_{\text{esc}} \). For \( f_{\text{esc}} = 0.05 \), the simulation box is fully ionized
at \( z = 5.8 \) in all models.

### 3. The Statistical Measures

#### 3.1. The Number of Neutral Segments

We are now in a position to compute the proposed statistics.
We begin with \( N(>L) \), the mean number of neutral (unionized)
segments of length greater than \( L \) in a given redshift range in a
line of sight (see Pentericci et al. 2002 and Barkana 2002 for
similar statistical measures). We have the spatial distribution
of ionized and neutral regions in the simulation as a function
of redshift, for each of our five reionization scenarios (see Ta-
ble 1). To compute \( N(>L) \), we choose several random “lines of sight”
in the output of the simulation at a given redshift. In each
line of sight, we identify the neutral segments and tabulate their
lengths, \( L \), in comoving \( h^{-1} \) Mpc. A line of sight is obtained by
starting from a grid point at the boundary of the simulation and
going around the boundary of a rectangular slice of perimeter
\( 4 \times 141 \ h^{-1} \) Mpc (comoving) until we return to the starting point.
(The shape of the path used to extract a line of sight makes no
difference to our results. Using a rectangular path helps reduce
the chance of pattern repetition.) This yields a total of 256 lines
of sight, each spanning a redshift range corresponding to 564
\( h^{-1} \) Mpc (comoving). We then compute the mean \( N(>L) \) from
these lines of sight. For convenience, we normalize \( N(>L) \) to a
redshift span of 1 \( h^{-1} \) Gpc by multiplying the direct result ob-
tained from the simulation by 1000/564. The \( N(>L) \) (normalized
to 1 \( h^{-1} \) Gpc) is shown in Figure 1 for \( z = 6.66 \) (top), 6.22 (middle),
and 5.8 (bottom). The panels to the left show \( N(>L) \)
computed for \( f_{\text{esc}} = 0.01 \) at these three redshifts. To the right,
we show curves computed with \( f_{\text{esc}} = 0.05 \) at \( z = 6.66 \) (top)
and 6.22 (middle) and a variable \( f_{\text{esc}}^{\text{var}} \) at \( z = 5.8 \) (bottom). We
have also computed \( N(>L) \) from lines of sight each of length
141 \( h^{-1} \) Mpc passing through the simulation box at random
positions and found very similar results to those shown in the
figure.

The cells of our computational grid are approximately

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\(^{7}\) BNSL considered several models for the variation of \( f_{\text{esc}} \) from galaxy to
galaxy. Here we adopt the simplest model, in which \( f_{\text{esc}} \) is constant for all
galaxies.

| Model | \( z \) | \( f_{\text{esc}} = 0.01 \) | \( f_{\text{esc}} = 0.05 \) | \( f_{\text{esc}}^{\text{var}} = 0.1 \) |
|-------|-------|----------------|----------------|----------------|
| A ..... | 6.66 | 0.155 0.612 | ... | ... |
| B ..... | 6.66 | 0.079 0.464 | ... | ... |
| C ..... | 6.66 | 0.458 0.892 | ... | ... |
| D ..... | 6.66 | 0.229 0.726 | ... | ... |
| E ..... | 6.66 | 0.183 0.648 | ... | ... |

Note.—Here we show the volume filling factor of ionized
regions in the simulation at \( z = 6.66, 6.22, \) and 5.80, for
two constant values of \( f_{\text{esc}} \) (cols. [3] and [4]) and a variable
fraction \( f_{\text{esc}}^{\text{var}} \) (col. [5]) that increases linearly with time from
0.01 at \( z = 6.22 \) to 0.1 at \( z = 5.8 \).

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\( L \), in comoving \( h^{-1} \) Mpc. A line of sight is obtained by
starting from a grid point at the boundary of the simulation and
going around the boundary of a rectangular slice of perimeter
\( 4 \times 141 \ h^{-1} \) Mpc (comoving) until we return to the starting point.
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difference to our results. Using a rectangular path helps reduce
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positions and found very similar results to those shown in the
figure.

The cells of our computational grid are approximately
of sight each of redshift span corresponding to $1\ h^{-1}\ \text{Gpc}$, as estimated from calculations using a lower resolution computational grid (1283 cells). Doubling the grid resolution to 5123 does not fully resolve the structure of gas in the IGM. From the simulation, we define a quantity $n(x)$ with ionizing luminosities sufficiently high to ensure the population density of galaxies from the simulation. We include only those galaxies that have been ionized and unity otherwise. We also use the cloud-in-cell method to derive the number density $n(x)$ of galaxies from the galaxy positions in the simulation. We include only those galaxies with ionizing luminosities sufficiently high to ensure the population is fully resolved in the $N$-body simulation. Because ionizing luminosity correlates only weakly with halo mass—since it depends so strongly on the star formation rate—this means we select only the most luminous sources—5.4, 10, and $11 \times 10^{54}\ h^{2}\ \text{photons s}^{-1}$ at $z = 5.8$, 6.2, and 6.7, respectively. These sources are rare and contribute only a small fraction to the total ionizing luminosity density of the universe (about 15% and 18% at $z = 6.22$ and 5.80, respectively). Denoting the average values of $n$ and $\bar{n}$ by $\bar{n}$ and $\bar{h}$, respectively, we define the cross-correlation, $\xi$, as

$$\xi(r) = \langle [n(x)/\bar{n} - 1][h(x + r)/\bar{h} - 1] \rangle,$$

where the angle brackets imply averaging over all grid points $x$. In practice, the calculation of $\xi$ is done using the technique of fast Fourier transforms. Figure 2 demonstrates that $\xi$ is sensitive to the ionization model. It is positive for model C (low density), almost vanishes for model D (random spheres), and is negative for models A, B, and E, which ionize dense regions first. However, $\xi$ has a similar shape for all the high-density models (A, B, and E), and we expect that it will be difficult to distinguish between them in observational data. Nevertheless, they all are significantly different from either model C or D. So $\xi$ should successfully discriminate among low-density, random ionization, and high-density models.

4. DISCUSSION

The statistic $N(>L)$, giving the number of neutral segments of length greater than $L$ for a given total length of a QSO spectrum, is sensitive to the filling factor and the way in which ionization proceeds. The cross-correlation between candidate ionizing sources and neutral regions is less sensitive to the filling factor but is a more direct and robust probe of the propagation of the ionization fronts. In addition to QSO spectra, the cross-correlation requires a sample of candidates (galaxies and QSOs) for the ionizing radiation. Catalogs of galaxies and QSOs at high redshift are rapidly accumulating, making it possible...
sible to compute the QSO-flux and galaxy-flux correlations. Comparison between galaxy-flux and QSO-flux correlation functions will tell us whether galaxies or QSOs contributed most of the ionizing radiation.

Current observations do not allow a robust determination of \( N(L) \). The number of spectra needed to determine \( N(L) \) to within a given accuracy can be estimated by noting that the relative error on this function is \( 1/\sqrt{MN} \), where \( M \) is the number of observed QSO spectra covering the same redshift range. Nevertheless, we still can make general conclusions based on the Becker et al. (2001) result, assuming that the long Gunn-Peterson trough they observe is indeed a signature of reionization. Let us take the length of a spectrum in the Ly\( \alpha \) forest at \( z \approx 6 \) to be \( \sim 250 \, h^{-1} \) Mpc, corresponding to the comoving distance between Ly\( \alpha \) and Ly\( \beta \) emission lines. An inspection of Figure 1 shows the following: (1) A completely neutral stretch of a comoving length of \( 60 \, h^{-1} \) Mpc at \( z \approx 6.2 \) is inconsistent with a large filling factor. (2) The observations indicate that the chances of finding long neutral regions at \( z < 5.94 \) are tiny, while they are significant at higher redshift. This behavior seems inconsistent with our theoretical \( N(L) \) computed with constant \( f_{\text{esc}} \). If \( f_{\text{esc}} = 0.01 \), then there are similar probabilities for finding long segments at \( z = 6.22 \) and \( z = 5.80 \). If \( f_{\text{esc}} = 0.05 \), then the box is fully ionized at 5.80, while at \( z = 6.22 \) long segments are very rare. Therefore, the data favor models in which there is a significant increase in the amount of ionizing radiation in the IGM, due to either an increasing escape fraction over this redshift range or a much stronger evolution in the galaxy/QSO population than is predicted by our model. (3) Our model C, in which ionization proceeds from low- to high-density regions, seems to be inconsistent with an \( \sim 60 \, h^{-1} \) Mpc neutral region, even for escape fractions as low as \( f_{\text{esc}} = 0.01 \).

We point out two caveats to the above discussion. First, model C assumes that reionization begins from the least dense regions. However, in cosmological simulations of radiative transfer (Gnedin 2000; Ciardi et al. 2000) reionization appears to begin from moderate density regions that are near the sources before proceeding to the lowest density regions. So model C (Miralda-Escudé et al. 2000) serves as only an approximation to the reionization process as seen in the simulations. The second caveat is that in observed spectra ionized regions with large optical depths can be confused with completely ionized regions and vice versa. By measuring Ly\( \beta \) absorption, lower limits of about 20 on the Ly\( \alpha \) optical depth can be obtained. Regions with large optical depth can arise in the presence of strong large-scale fluctuations in the ionizing background. To estimate the degree of the confusion, we have computed \( N(L) \) assuming that regions with optical depth larger than 20 are identified as ionized. We found that in this more detailed calculation \( N(L) \) is shifted to smaller \( L \) by less than a factor of 2 at large \( L \). At small \( L \), \( N(L) \) is reduced by a factor of less than 2, although this could likely be reduced with a more careful analysis, as suggested above. Nevertheless, the effect of fluctuations in the ionizing background on QSO spectra still needs to be quantified in detail.

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