Abstract

Observations of QSOs at $z \sim 5.7 - 6.4$ show the appearance of Gunn-Peterson troughs around $z \sim 6$, and a change in the slope of the IGM optical depth $\tau(z)$ near $z \sim 5.5$. These results are interpreted as a signature of the end of the reionization era, which probably started at considerably higher redshifts. However, there also appears to be a substantial cosmic variance in the transmission of the IGM, both along some lines of sight, and among different lines of sight, in this intriguing redshift regime. We suggest that this is indicative of a spatially uneven reionization, possibly caused by the bias-driven primordial clustering of the reionization sources. There is also some independent evidence for a strong clustering of QSOs at $z \sim 4 - 5$ and galaxies around them, supporting the idea of the strong biasing of the first luminous sources at these redshifts. Larger samples of high-$z$ QSOs are needed in order to provide improved, statistically significant constraints for the models of these phenomena. We expect that the Palomar-Quest (PQ) survey will soon provide a new set of QSOs to be used as cosmological probes in this redshift regime.

Key words: reionization, structure formation, quasars, cosmic variance

1 Introduction

Understanding of the cosmic reionization era – from the appearance of the first luminous sources perhaps at $z \sim 20$, to the end of the IGM phase transition from neutral to essentially fully ionized hydrogen at $z \sim 6$ – is now perhaps the focal arena of cosmology. This field connects a number of fundamental astrophysical processes, formation of the first stars, galaxies, AGN, and large-scale structure, and their effect on the early IGM, more than any other redshift range studied so far. For recent reviews see, e.g., [28, 1, 34, 18].

There are so far three kinds of observational constraints on the nature and extent of the reionization era. Historically the first was the evidence of the
approach to the reionization, or its final stages, at $z \sim 6$ from the spectra of QSOs in this redshift range (4, 19, 21, 1342).

The primary evidence is the existence of Gunn-Peterson (hereafter GP) (23) absorption troughs in the spectra of $z > 6$ QSOs. Such features are now seen along all lines of sight at $z > 6$ where adequate data exist. There is also a growing evidence for a change in the slope of the optical depth vs. redshift, $\tau(z)$ (20, 42) around $z \sim 5.5 - 6$, indicating that some qualitative change in the physics and geometry of IGM occurs at these redshifts. Transition from the thickening of the normal Ly$\alpha$ forest out to $z \sim 5$ to the UV-opaque IGM at $z \sim 6$ is fairly dramatic (see Fig. 1). As discoveries of more such objects continue (22), spectroscopy of high-$z$ QSOs remains one of the principal empirical approaches to mapping of the final stages of reionization.
The picture was complicated by the evidence for an early reionization at $z \sim 10 - 20$ from the CMBR measurements by the WMAP satellite (27). While the confirmation of this important result is still to come, we note that it is not necessarily contradictory to the QSO results: the history of the luminous sources and their effect on the IGM was probably highly complex, and there was a finite time interval from the appearance of the first sources of UV photons at the end of the cosmic dark ages, and the completion of the reionization phase transition a few hundred million years later.

In parallel, a number of groups have studied star-forming galaxies at $z \sim 6 - 7$, and measurements of the Ly$\alpha$ emission line luminosity function evolution provide another useful observational constraint (30; 39). While the QSO absorption spectra probe the neutral hydrogen fraction regime $x_{HI} \leq 10^{-2}$, this method is sensitive to the range $x_{HI} \sim 10^{-1} - 10^0$.

In the future, using H I hyperfine transition line at 21 cm promises to be another powerful probe of the earlier stages of reionization, as reviewed in a number of talks at this conference. Detection and spectroscopy of GRB afterglows from the first generations of massive stars will be another spectacular method to study the astrophysics of reionization.

If, as both the data and theory now suggest, the distribution of the first luminous sources was highly clustered, leading to a spatially uneven reionization phase transition, direct measurements of the primordial clustering would provide a complementary insight into the overall picture. Luminous QSOs at these redshifts are potentially a powerful probe of such bias-driven clustering; see, e.g., (18) and references therein.

Here we review some of the current evidence for a spatially inhomogeneous reionization, and the possible uses of high-$z$ QSOs to study the late stages of this fundamental cosmological era. In some ways, QSOs provide unique observational constraints, and are in many ways complementary to other approaches. We also outline some possibilities for the future work.

2 Evidence for a Clumpy Reionization?

The reionization era must be extended in redshift, from the time the first luminous sources turn on, to the final percolation of the reionized bubbles universe-wide. At any given intermediate redshift, there will be some spatially uneven distribution of the neutral and ionized IGM, whose characteristic physical scales and topology will depend on the clustering and luminosity histories of the local reionization sources. In principle, such variations in the geometry/topology of reionization should be detectable as variations in the IGM
transmission, both along and among different lines of sight to sources still within the incomplete reionization regime.

Such variations are indeed observed, and can in principle be used to place quantitative constraints on theoretical models (14, 15); see Figs. 2 and 3. Measurements of the Lyα and Lyβ optical depth to a number of SDSS high-z QSOs suggest a comparable cosmic variance in the IGM transmission in this redshift regime (11).

What is interesting here is that there may be an apparent increase in the cosmic variance of the IGM transmission as one approaches the ostensible end-of-the-reionization redshift, $z \sim 6$. The variance is impossible to measure...
Fig. 3. The behavior of the transparency of the IGM at high red shifts, shown as the transmission on the left, and as the optical depth on the right. The bottom panels indicate the number of lines of sight used at every redshift. The solid lines indicate the mean, and the hashed areas the spread among the different lines of sight. The data have been smoothed with a Gaussian with a $\sigma(z) = 0.02$; a wider smoothing or binning, preferred by some authors, can wash out important features. Note the change in the slope of $\tau(z)$ around $z \approx 5.8$; this corresponds to the dramatic change in the ionizing flux and the fraction of the neutral hydrogen at these redshifts (20), which is interpreted as the signature of the end of the reionization era. There is also a hint that the spread among different lines of sight (i.e., the cosmic variance in the IGM absorption properties) increases just before the reionization redshift is reached. From [14; 18].

as the flux disappears at higher redshifts, but of course a substantial variation in the neutral hydrogen fraction could be present in the optically thick regime; this calls for some alternative measurement methodology.

Interestingly, high quality QSO spectra at $z > 6$ can be used to measure the sizes of the H II regions around these objects, and then to constrain the neutral hydrogen fractions in the regime $x_{HI} \sim 10^{-1} - 10^0$ [44, 33]. From a single QSO, Wyithe & Loeb conclude that $x_{HI} > 10^{-1}$ in its vicinity. However, this is the $x_{HI}$ range also probed by the census of the Ly$\alpha$ emitters [30, 39], where the preliminary results indicate $\langle x_{HI} \rangle < 10^{-1}$ in the general field. There are both small number statistics and interpretative uncertainties in both methods, and clearly at least a few more QSO Strömgren sphere measurements are needed. If the two approaches continue to give systematically different results as the data accumulate, that may be indicative of systematic differences in the large-scale environments, e.g., with QSOs being situated in particularly dense regions.
A strong spatial nonuniformity in the final stages of reionization could be caused by a strong clustering of the reionization sources. Since there was not enough time for a substantial large scale structure growth at these redshifts, the clustering would have to be primordial, e.g., reflecting a generic biased galaxy formation scenario, where the first luminous sources form in and around the highest peaks of the primordial density field, which are a priori strongly clustered almost regardless of any details of the assumed structure formation models (26). Thus, we expect that there was a fundamental connection between the early structure formation and the geometry and topology of the reionization, as reflected in the cosmic variance of the IGM transmission at these redshifts.

3 QSOs as Markers of the Primordial Large-Scale Structure

There is now a substantial and growing evidence for a strong bias among the field galaxies at redshifts approaching 6; see, e.g., (18) for a review and references. This is entirely as expected from models of biased galaxy formation.

Many or all luminous QSOs at these redshifts are also likely situated in massive host galaxy halos. This is suggested by the high masses of their central black holes \((M_\bullet > 10^9 M_\odot)\); see, e.g., (43; 7; 32); as well as their highly evolved chemical abundances (24; 25; 31; 8; 9). Direct observations of circum-QSO regions at \(z > 4\) show a considerably enhanced density of star forming galaxies in their vicinity (10; 11; 12; 40) consistent with the idea that luminous high-z QSOs may mark sites of future rich clusters of galaxies.

QSOs themselves appear to be strongly clustered at these redshifts; see (13; 18) and references therein. The implied clustering lengths are comparable to those of the rich clusters today, tens of Mpc. An even more intriguing possibility is that QSO clustering at \(z > 4\) extends to physical scales of \(\sim 100 - 200 h^{-1}\) comoving Mpc (10; 12). These highly preliminary, uncertain, but suggestive results must be confirmed by careful analysis of statistical samples of high-z QSOs.

If QSO clustering at \(z \sim 4 - 6\) is real, it has to be bias-driven. It would be a nearly unique probe of the clustering of luminous sources at these redshifts, on physical scales \(\sim 10 - 100\) comoving Mpc, and directly relevant for the interpretation of the cosmic variance of IGM transmission at the end of the reionization.

Also, if substantial spatial variations in the distribution of the ionized gas existed at these redshifts, they might have also left an observable imprint in the CMBR fluctuations, essentially the clustered S-Z effect. In this context, it is
intriguing to recall the excess power at high angular frequencies, corresponding to the comoving separations of \( \sim 10 - 20 \) Mpc at the CMBR photosphere; see (35) and references therein.

4 The Palomar-Quest Survey

As the preceding discussion indicates, substantially larger samples of high-
\( z \) QSOs in the late- and post-recombination redshift regime are needed in order to provide better observational constraints on the physical parameters, geometry, and evolution of the IGM in this crucial era, as well as to quantify better the early, possibly highly biased large-scale structure.

The Palomar-Quest (PQ) Digital Synoptic Sky Survey (36; 3; 37; 29; 16; 17) will be a major new provider of high-
\( z \) QSOs at \( z \sim 4 - 6.5 \). The PQ survey is a collaborative effort between Yale, Caltech, Indiana University and NCSA in the USA, with collaborations with INAOE in Mexico, and other groups. The data are taken at the 48-inch Samuel Oschin Schmidt telescope at Palomar Observatory, using a special 112-CCD camera built for this purpose. The data rate is about 1 TB per month. Data are reduced and archived at multiple locations (Caltech, NCSA, Yale). National Virtual Observatory (NVO) standards, protocols, and connections are built in from the start, and will facilitate a very broad data access and analysis.

Approximately 50% of the time is used for PQ survey drift scans, and the rest is used largely in the traditional point-and-stare mode by groups at JPL and Caltech for exploration of the Solar System. In the drift scan mode, the PQ survey covers strips \( \sim 4.6^\circ \) wide at a constant Dec, with an area coverage of \( \sim 500 \) deg\(^2\) per clear night, in 4 filters. The pixel scale is 0.878 arcsec. The scans are obtained in the range \(-25^\circ \leq \delta \leq +25^\circ\), giving the total useful survey area of \( \sim 15,000 \) deg\(^2\). About a third of the survey area overlaps with that of SDSS, thus providing a valuable cross-check and cross-calibration. The survey uses two sets of filters, the traditional \( UBRI \), and the SDSS \( r' i' z' \), with about an equal time share in each. Typical limiting magnitudes in a single pass in good conditions are: \( r' \sim 21.5 \) mag, \( i' \sim 20.5 \) mag, \( z' \sim 19.5 \) mag, \( R \sim 22.0 \) mag, and \( I \sim 21 \) mag. Coadding of about 6 passes reaches the depths comparable to SDSS. As the survey unfolds, we anticipate that we will cover much of the area to at least a magnitude deeper, and a subset of the total survey area deeper yet.

One of the key scientific goals of the PQ survey is the discovery of a significant number of high-
\( z \) QSOs, to be used as a statistical sample for studies of early structure formation and reionization. The methodology is identical to that used by SDSS, DPOSS, and other multi-color high-
\( z \) QSO surveys...
to date, using colors as discriminants for objects classified as point sources in the images. High-z QSO candidates are identified in the PQ data using $BRI'r'i'z'$ colors, which in appropriate combinations can be used to find QSOs at $z \sim 4 - 6.5$. IR photometry is necessary to separate QSO candidates at $z > 5.5$ from late-M and brown dwarfs. We use coadds of 2MASS images to eliminate some of the brighter dwarf contaminants, but most candidates require a deeper IR imaging. This is currently obtained at the Yale SMARTS telescopes at CTIO, and at the INAOE/OAGH 2.1-m telescope at Cananea, Mexico. The surviving color-selected candidates are then followed spectroscopically at the Palomar 200-inch telescope, and QSOs at $z > 5$ are selected for deeper and more extensive follow-up studies at the Keck and other facilities.

The first high-z QSOs have been found, but the survey is still in an early stage. We anticipate that we will double the sample of the SDSS high-z QSOs over the next few years. Studies of the joint SDSS+PQ sample will be used to provide new observational constraints for structure formation at $z \sim 4 - 6.5$, and late stages of reionization at $z \sim 6$.

5 Concluding Comments

As the reionization becomes complete, the residual H I fraction rapidly drops over large spatial scales. QSO absorption spectra are the only currently known probe of this IGM regime, $\langle x_{HI} \rangle \leq 10^{-2}$. If this happens at $z \sim 6$, as the data seem to indicate, then spectroscopy of QSOs in this redshift regime will remain a unique probe of the late stages of reionization for some time to come.

Moreover, the data indicate that a considerable cosmic variance is present in the transmission properties of the IGM at these redshifts, along different lines of sight. If the characteristic physical scales of the late reionization topology are in the range of tens to hundreds of comoving Mpc, as the recent theoretical studies suggest (2, 45, 35), then statistically significant samples of QSOs will provide the first solid observational constraints for theoretical models.

If there is indeed a substantial, bias-driven clustering of the luminous sources responsible for the reionization (which would then naturally be spatially clumpy and lead to the observed cosmic variance in the IGM transmission properties), QSOs may again prove to be useful probes of such clustering, especially if they are associated with some of the densest peaks of the density field at the time. Until galaxy redshift surveys at $z \sim 6$ start spanning comparable comoving volumes and $>>$ 100 comoving Mpc scales – which may be a while in coming – QSOs may be again the only viable probe of such primordial clustering and biasing.
Therefore, we expect that studies of larger high-$z$ samples than currently available, coming from SDSS, PQ, and other surveys, will continue to generate even more significant observational constraints for the models, leading to a better physical understanding of the final stages of the reionization era.

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