BLACK HOLES FROM THE DARK AGES:
EXPLORE THE REIONIZATION ERA
AND EARLY STRUCTURE FORMATION
WITH QUASARS AND GAMMA-RAY BURSTS

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The cosmic reionization era, which includes formation of the first stars, galaxies, and
AGN, is now one of the most active frontiers of cosmological research. We review briefly
our current understanding of the early structure formation, and use the ideas about a
joint formation of massive black holes (which power the early QSOs) and their host galax-
ies to employ high-redshift QSOs as probes of the early galaxy formation and primordial
large-scale structure. There is a growing evidence for a strong biasing in the formation
of the first luminous sources, which would lead to a clumpy reionization. Absorption
spectroscopy of QSOs at $z \geq 6$ indicates the end of the reionization era at $z \sim 6$; yet
measurements from the WMAP satellite suggest an early reionization at $z \sim 10 - 20$.
The first generation of massive stars, perhaps aided by the early mini-quasars, may have
reionized the universe at such high redshifts, but their feedback may have disrupted the
subsequent star and galaxy formation, leading to an extended and perhaps multimodal
reionization history ending by $z \sim 6$. Observations of $\gamma$-ray bursts from the death events
of these putative Population III stars may provide essential insight into the primordial
structure formation, reionization, early chemical enrichment, and formation of seed black
holes which may grow to become central engines of luminous quasars.

1. Introduction. The End of the Cosmic Dark Ages

Exploration of the cosmic reionization era – from the appearance of the first lu-
minous sources to the end of the phase transition when the intergalactic hydrogen
becomes fully reionized and transparent to the UV light – is now rapidly becoming
an active frontier of cosmological research. a This fundamental cosmological era
signals the appearance of first luminous sources, including the first population of
stars and their explosive ending events, the first galaxies, and the early AGN. In
this review we describe some the current ideas and recent results in this field, with
an emphasis on the use of high-redshift quasars (QSOs) and $\gamma$-ray bursts (GRBs)
as probes of the early structure formation and reionization.

aWe use the term reionization era for an extended period of time lasting a few hundred million
years, from the formation of the first luminous sources at $z \sim 20 - 30$, to the final conversion
of the cosmic hydrogen from neutral to ionized state at $z \sim 6$, rather than a much shorter period
of time when that phase transition is completed universe-wide (a somewhat ill-defined concept),
which we could call the reionization epoch.
There are two main streams of cosmology: the traditional one, which originated with Hubble, which aims to measure the values of parameters which describe the global geometry and kinematics of the universe; and a quest to understand the formation and evolution of the major constituents of the universe on large scales, galaxies and the large-scale structure (LSS). The task of the former is now essentially complete, with the values of cosmological parameters measured with a percent-level precision from the studies of the cosmic microwave background (CMBR) fluctuations, along with the data from SN Hubble diagrams, LSS surveys, etc. There is also an elegant tributary stream of physical cosmology which tackles the early universe, from the Planck era, through the inflation era, cosmic nucleosynthesis, and a detailed analysis of the CMBR fluctuations at the recombination epoch. But the second major stream of cosmology, understanding of the structure formation and evolution, remains as a messy, difficult, and challenging enterprise.

Nevertheless, there has been a remarkable progress in our understanding of galaxy and structure formation in the past several years. The general hierarchical picture of galaxy and structure formation is now firmly established, both observationally and theoretically. However, as is always the case in cosmology, the clarity and certainty of our knowledge fade as the look-back time and distance increase. While we have a fairly solid grasp of galaxy evolution out to $z \sim 1$, and some insights out to $z \sim 4 - 5$, the early, formative stages of the cosmic structure, say within the first 1 Gyr after the Big Bang, remain murky and are now becoming a focal arena of cosmological research.

An increasing number of necessarily young (due to their high redshifts) galaxies are being discovered. As of mid-2004, there are several tens of spectroscopically confirmed objects at $z > 5$ (e.g., Dey et al. 1998; Weymann et al. 1998; Spinrad et al. 1998; Ellis et al. 2001; Dawson et al. 2002; Rhoads et al. 2003; Stanway et al. 2004; Hu et al. 1998, 2004; etc.), and a rapidly growing number of objects at $z > 6$ (e.g., Hu et al. 2002; Cuby et al. 2003; Kodaira et al. 2003; Kneib et al. 2004; Kurk et al. 2004; Stern et al. 2004; etc.), with an even larger number of color-selected candidates which may be at comparable redshifts. These discoveries are providing us with some direct insights into the early stages of galaxy and LSS formation.

Theoretical reviews include, e.g., Loeb & Barkana (2001), Barkana & Loeb (2001), and Miralda-Escudé (2003a). In a nutshell, the currently believed scenario is as follows. When the Universe was about 380,000 years old, at a redshift $z_{\text{rec}} \sim 1100$, it underwent a phase transition, from an incandescent plasma containing the heat of the Big Bang, to a space filled with dark matter, energy and neutral gas. The Universe then entered the “dark ages”, with embryonic structures growing from the seeds of dark-matter fluctuations, which are observed today as ripples in the CMBR. After a few hundred million years, these condensations became dense enough for the first stars to form, leading to the appearance of the first galaxies and the growth of the massive black holes that are believed to power quasars.
Figure 1. A schematic outline of the early cosmic history, according to our current understanding. Approximate redshifts of key epochs are indicated on the left, and converted to the corresponding ages using the now standard Friedmann-Lemaître cosmology with $h = 0.7$, $\Omega_0 = 0.3$, and $\Lambda_0 = 0.7$. Needless to say, we have a very poor understanding of what really happened during the reionization era, and when it actually started; but we are pretty sure that it ended by about $z \sim 6$.

As these first objects lit up, they also modified the gas between them, ionizing the hydrogen and making it transparent to ultraviolet light. The universe underwent another phase transition, from a neutral to an ionized state. Each of the primordial sources of light - most powered by young, massive stars, but some powered by the accretion of matter into growing black holes (the early quasars) - excavated a Strömgren bubble of ionized gas in the otherwise neutral surrounding medium. When these bubbles began to percolate, the reionization was complete.

The standard observational test of the approach to reionization is the prediction of an extended, optically thick absorption due to neutral hydrogen at $\lambda_{\text{rest}} < 1216$ Å (Gunn & Peterson 1965; hereafter GP), as distinct from the usual Lyα forest due to a multitude of distinct hydrogen clouds embedded in a largely ionized intergalactic medium (IGM) as observed at lower redshifts. Indeed, the GP effect was recently observed in a spectrum of quasar SDSS 1030+0524 at $z = 6.28$ (Becker et al. 2001; Fan et al. 2001; see also Pentericci et al. 2002, Djorgovski et al. 2001, 2002, and in prep.). Such absorption troughs are now seen along every line of sight to QSOs at $z > 6$. However, there are some interpretative complications remaining.
The first protogalactic starbursts probably appeared at $z \sim 20 - 30$. They may have reionized the universe by $z \sim 15 \pm 5$, as indicated by the recent WMAP measurements (Kogut et al. 2003). The history of the IGM, ionizing flux, and early galaxy and AGN formation from that point on is extremely uncertain and was probably very complex; it is even possible that the universe was reionized twice (Cen 2003; Wyithe & Loeb 2003b; Sokasian et al. 2004; etc.). The evolution of the mean ionizing flux with redshift is expected to be very strong, due to the gradual appearance and growth of the sources (protogalaxies and early AGN) responsible for the reionization.

It is now generally believed that the reionization sources were mainly star-forming galaxies rather than AGN, and recent studies indicate an already vigorous star formation at $z \sim 6$ (Giavalisco et al. 2004; Dickinson et al. 2004; Stanway et al. 2004; Bouwens et al. 2004; Bunker et al. 2004; Stiavelli et al. 2004; etc.). However, it is also possible that a substantial early AGN (“mini-quasar”) activity may predate the peak epoch of star formation in galaxies (Silk & Rees 1998; Madau & Rees 2001).

The reionization era is a major cosmological milestone. It signals the appearance of the first galaxies and AGN, in the epoch of “cosmic renaissance”. The spatial and temporal structure of the IGM phase transition reflects the primordial large-scale structure and the early luminosity and density evolution of the reionization sources, the primordial starbursts and AGN. A good understanding of the structure and extent of the reionization is important by itself, reflecting the earliest phases of structure formation, and for modeling of CMBR foregrounds at high angular frequencies, a subject of an increasing cosmological interest. We are now just starting to probe this fundamental cosmological era.

2. The Quasar-Protogalaxy Connection

There are now several compelling and growing lines of evidence that there are fundamental connection between the formation and evolution of galaxies and their central massive black holes, which presumably powered the early quasar activity. Along with the established uses of QSOs as absorption probes of the IGM, this suggest their use as direct probes and markers of sites of early, massive galaxy formation and primordial LSS. For a review and references, see, e.g., Djorgovski (1999).

Physically, it is now believed that the same kind of processes, i.e., dissipative mergers and tidal interactions, may be fueling both bursts of star formation and AGN activity (see, e.g., Norman & Scoville 1988, Sanders et al. 1988, Carlberg 1990, Hernquist & Mihos 1995, Mihos & Hernquist 1996, Franceschini et al. 1999, Monaco et al. 2000, Kauffmann & Haehnelt 2000, etc.; see, e.g., Haehnelt 2004 for a recent review).

Quasars thus may be a common phase of the early formation of ellipticals and massive bulges. QSO demographics support this idea (Small & Blandford 1992,
Chokshi & Turner 1992, Haehnelt & Rees 1993; see Richstone 2004 for a review). There should be dead (actually only sleeping) QSO remnants, supermassive black holes (SMBH), in most of the massive galaxies today.

Indeed, most or all ellipticals and massive bulges at $z \sim 0$ seem to contain central massive dark objects, presumably SMBH, suggestive of an earlier QSO phase (see, e.g., Kormendy 2004, Kormendy & Richstone 1995, for reviews and references). Their masses correlate in a roughly direct proportion with the masses of luminous old stellar components of their host galaxies (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Merritt & Ferrarese 2001), with typical mass fractions $M_\bullet/M_\star \sim 10^{-3}$. The inferred mean comoving density of these putative QSO remnants, $\rho_\bullet \sim 5 \times 10^5 M_\odot Mpc^{-3}$, is also in a good agreement with the completely independent estimates obtained from integration of the total QSO light out to high redshifts, with reasonable assumptions about the radiative efficiency of mass accretion (Soltan 1982, Small & Blandford 1992, Salucci et al. 1999, etc.).

Moreover, there are even better correlations with the stellar dynamics of the hosts on a scale of a few kpc, $M_\bullet \sim \sigma_4^{1.5}$ (Ferrarese & Merritt 2000; Gebhardt et al. 2000), whereas the SMBHs have radii of the order of $10^{-4}$ pc; and with the masses of the host galaxy halos, on the scales of $\sim 10^5$ pc, with typical $M_\bullet/M_\star \sim$ few $\times 10^{-5}$ (Ferrarese 2002a). It is intriguing that the observed slope of this relation, $M_\bullet \sim M_\text{halo}^{1.6}$, is close to that predicted in the model by Haehnelt et al. (1998). Note that the relation implies that more massive – and also less dense – host halos are much more effective in forming and/or growing SMBHs; and there may be even a threshold halo mass needed for a presence of a SMBH. For a good review of these issues, see, e.g., Ferrarese (2002b). A successful theoretical model needs to explain both the slopes of these relations, and account for a remarkably small intrinsic scatter. In any case, these correlations strongly suggest a co-formation and co-evolution of galaxies and their central SMBHs, with some as-yet poorly understood feedback mechanisms playing an important role.

Additional clues come from the measurements of the metallicities and abundances in QSO broad emission line regions. High metallicities (up to $10 \times Z_\odot$) observed in $z > 4$ quasars (Hamann & Ferland 1993, 1999; Matteucci & Padovani 1009; Dietrich et al. 2003a) are indicative of a considerable chemical evolution involving several generations of massive stars in a system massive enough to retain and recycle their nucleosynthesis products, e.g., comparable to the cores of giant ellipticals (Romano et al. 2002). This is also supported by detections of copious amounts of molecular gas and dust in large numbers of high-$z$ QSOs (Guilloteau et al. 1999; Omont et al. 2001; Bertoldi et al. 2003a,b; Walter et al. 2003; etc.)

Intriguingly, the relative abundances of the $\alpha$-group elements, which are produced predominantly by the Type II SNe (exploding massive stars), and Fe-group elements, which are contributed mainly by the type Ia SNe (detonating white dwarfs) show an enhanced Fe/Mg ratios out to $z \sim 5$. Since there should be some delay (perhaps a few $\times 10^8$ yr?) between the onset of star formation and the average explosion
time for the progenitors of Type I SNe, this suggests that the star formation in the hosts of these QSOs started at even higher redshifts, perhaps at \( z > 10 \) (Dietrich et al. 2003b), making them possibly significant contributors to reionization.

Finally, estimates of the SMBH masses powering high-z QSOs indicate that objects with \( M_\bullet > 10^9 M_\odot \) are present even out to \( z \sim 5 - 6 \) (Willott et al. 2003; Dietrich & Hamann 2004; McLure & Dunlop 2004). This can be alleviated, but only slightly, by invoking beaming (which does boost the apparent continuum luminosity, but does not affect the line velocity widths, both of which are used in estimating the \( M_\bullet \) in QSOs), or gravitational lensing (ditto; and we also know that only a small fraction of bright QSOs, \( \sim \) a few \( \times 10^{-3} \), are strongly lensed). While the evolution of the \( M_\bullet/\text{M}_\text{halo} \) relation out to such high redshifts is highly uncertain at this time, these QSOs are likely situated in very massive hosts, e.g., with \( \text{M}_\text{halo} \sim 10^{12} - 10^{13} M_\odot \) (see also Turner 1991 for a prescient discussion of these matters). Such massive halos should be rare, and may be associated with \( \sim 4 \) to 5-\( \sigma \) peaks of the primordial density field, and thus be highly biased (Efstathiou & Rees 1998, Cole & Kaiser 1989, Nusser & Silk 1993, etc.), possibly marking the cores of future rich clusters.

Overall, there is now a compelling evidence for a co-formation and co-evolution of SMBHs (QSO engines) and their host galaxies. More details and references can be found, e.g., in the proceedings dedicated to this topic, edited by Ho (2004).

3. The Evidence for a Strongly Biased Early Galaxy Formation

One essential aspect of the early galaxy and structure formation is that it should be very uneven spatially, starting at the highest peaks of the primordial density field, and then spreading out. This is a generic prediction in essentially all modern models of galaxy formation, resting only on the reasonable assumption that star and galaxy formation will start in the densest regions first. The most massive density peaks in the early universe, and the luminous objects forming in or near them, are likely to be strongly clustered \textit{a priori} (Kaiser 1984), and thus represent biased tracers of the density field. The early formation of galaxies should be closely related to the primordial large-scale structure.

The evidence for such a bias is already seen with large galaxy samples at \( z \sim 3 - 3.5 \) (Steidel et al. 1998, Adelberger et al. 1998, etc.), while normal galaxies at \( z \sim 0 \) seem to be relatively unbiased tracers of the mass (see, e.g., Lahav et al. 2002, or Verde et al. 2002). The biasing should be stronger at earlier times, and for the more massive systems, as indicated in numerous theoretical studies (e.g., Brainerd & Villumsen 1994, Matarrese et al. 1997, Moscardini et al. 1998, Blanton et al. 2000, Magliocchetti et al. 2000, Valageas et al. 2001, etc.). It is then expected that biasing should be very strong for the first massive protogalaxies, some of which may be the hosts of quasars at \( z \sim 4 - 6 \), and beyond. Observations indeed confirm this prediction in at least two ways:

First, an “excess” in the number of galaxies and in the density of star formation
Figure 2. A schematic illustration of biasing. What is shown is a hypothetical cut through the primordial density field, with a mean value $\langle \rho \rangle$. Density fluctuations exist on all spatial scales, and the densest spots, say above some critical density threshold $\rho_*$, correspond to the smaller peaks riding atop of the larger waves. Such dense spots – which are the most likely sites of early star, galaxy, and AGN formation – are naturally clustered, and may be plausible progenitors of future rich clusters. They are the brightest, but highly biased representatives of the overall density field. As the time goes on, fluctuations in less dense regions become dense enough to ignite star formation, until the entire volume is populated by galaxies.

(Perhaps up to two orders of magnitude more than in the general field at comparable redshifts) was also seen in a systematic Keck survey of fields centered on the known $z > 4$ quasars (Djorgovski 1998, 1999; Djorgovski et al. 1999; and in prep.), consistent with the idea that luminous high-$z$ QSOs may mark sites of future rich clusters of galaxies.

Second, high-$z$ QSOs themselves appear to be strongly clustered. The first hints of such an effect at high redshifts were provided by the three few-Mpc quasar pairs at $z > 3$, found in the statistically complete survey by Schneider et al. (1994b), as first pointed out by Djorgovski et al. (1993), and subsequently confirmed by more detailed analysis (Kundic 1997, Stephens et al. 1997). Several serendipitously discovered QSO pairs at $z > 4$ have been found (Schneider et al. 1994a, Schneider et al. 2000, Djorgovski et al. in prep.), and a few-Mpc QSO pair at $z \approx 5$ was found by Djorgovski et al. (2003a). Chance probabilities of finding any one such QSO pair are estimated to be in the range $10^{-8} - 10^{-4}$; finding so many of them appears to be extremely unlikely if QSOs are not physically clustered. Intriguingly, the frequency of the few-Mpc separation quasar pairs at lower redshifts is roughly what may be expected from normal galaxy clustering (Djorgovski 1991; see also Zhdanov & Surdej 2001).

A substantial decrease in the clustering strength is expected at higher redshifts, since in any model gravitational clustering is always expected to grow in time. Yet, the inferred likely values of the clustering length for high-$z$ QSOs implied by these
observations are in tens of Mpc, much higher that at $z \sim 0$. The most natural explanation for this apparent paradox is that high-$z$ QSOs represent highly biased peaks of the density field, and that the bias itself evolves in time, as expected from theory. See, Djorgovski et al. (2003a) for a discussion and references.

The evidence for an increased bias at higher redshifts is not confined to QSOs: clustering of Ly$\alpha$ emitters at $z \sim 5$ in the Subaru Deep Field (Ouchi et al. 2003, 2004; Shimasaku et al. 2003, 2004).

On even larger physical scales, a very intriguing result was found in the DPOSS high-$z$ QSO survey (Djorgovski 1998, 1999, and in prep.). We found an unexpectedly large frequency of QSO pairs and triplets with the typical comoving separations of $\sim 100 - 200h^{-1}$ Mpc. The typical projected separations of the PSS QSO pairs are $< 2^\circ$, while the mean surface density at the depth of our survey implies r.m.s. $\sim 10^\circ$. The statistical significance of this effect is still difficult to quantify, mainly due to the possible systematics which could, at least in principle, produce a spurious clustering signal, e.g., slight variations in the survey depth, completeness of the QSO selection, etc., but it is estimated to be in the range $\sim 3 - 7 \sigma$.

If this is a real superclustering signal, its implications would be profound. It would represent a primordial (very) large scale structure, delineated by some of its highest, biased peaks containing quasars, only a few hundred physical Mpc away from the CMBR photosphere. It is very intriguing that the characteristic scale ($\sim 100 - 200h^{-1}$ comoving Mpc) implied by our measurements so far is so close to the physical scale of the horizon at the recombination (i.e., the first Doppler peak in CMBR fluctuations), and the characteristic scale of superclustering found in at least some redshift surveys (Broadhurst et al. 1990, Landy et al. 1996).

If the first luminous sources (galaxies and AGN) were strongly clustered due to biasing, then the structure of the IGM phase transition corresponding to the reionization was also very clumpy; we examine some evidence for the uneven reionization below. This is generally expected from theory (see, e.g., Barkana & Loeb 2004), but we also note that many current numerical simulations may not be sampling a sufficient comoving volume to probe such effects (Ciardi et al. 2000, Gnedin 2000, etc.).

4. Reionization, the Cosmic Renaissance

The appearance of first luminous sources at $z \sim 20 - 30$ ends the cosmic dark ages which start at the recombination, at $z \sim 1100$. As the numbers and luminosities of the first sources increase, ultimately there are enough ionizing photons produced to reionize most of the intergalactic hydrogen, a process we now know is complete by about $z \sim 6$ (the reionization of the intergalactic helium takes a while longer, until the buildup of the QSO population produces enough harder photons needed for that conversion; see, e.g., Wyithe & Loeb 2003a).

The early phases of formation of the first stars, protogalaxies, QSOs, and LSS, and the early physical and chemical evolution of the IGM are thus intrinsically
connected in a complex interplay of astrophysical processes and feedbacks. The onset and the finale of the reionization of hydrogen provide useful and physically meaningful time pegs, and thus we call this cosmic renaissance the reionization era; but we could just as well call it the early structure formation era, or the protogalactic era, or something else equally appropriate. This era is now becoming the new frontier of observational and theoretical cosmology.

As already noted, some combination of the young, massive stars and accretion processes associated with the first generation of embryonic AGN produces the necessary ionizing flux for the reionization (e.g., Miralda-Escudé 2003b), with stars almost certainly dominant near the end, at $z \sim 6$. Direct searches for ionizing sources at $z \sim 6 - 30$ will thus provide essential insights into the nature and evolution of this population.

One important question is whether Ly$\alpha$ line can be detected from objects embedded in a still largely neutral IGM. Since Ly$\alpha$ photons injected into a neutral IGM are strongly scattered, the red damping wing of the GP trough should strongly suppress, or even completely eliminate, the Ly$\alpha$ emission line (Miralda-Escudé 1998; Miralda-Escudé & Rees 1998; Loeb & Rybicki 1999). Subsequent calculations (e.g., Haiman 2002, Santos 2004) show that even for faint sources with little ionizing continuum, a sufficiently broad ($\Delta v \geq 300 \text{ km s}^{-1}$) emission line can still remain observable. The transmitted fraction depends upon the size of the local cosmological H II region surrounding a source, and therefore on the ionizing luminosity and age of the source. Presence of clustered fainter sources and possibly also previously active AGN in the vicinity of Ly$\alpha$ emitters would also facilitate the escape of Ly$\alpha$ photons (Wyithe & Loeb 2004b). Such young galaxies would then be detectable well into the reionization era.

The newly generated population of free electrons also leaves an imprint on the CMBR through Thompson scattering, and this signal has been indeed observed by the WMAP satellite (Kogut et al. 2003), suggesting a surprisingly high optical depth ($\tau \approx 0.17$) and consequently a high redshift for the reionization epoch, $z \sim 10 - 20$. It would be interesting to see whether the future CMBR observations and analysis confirm this result.

QSO absorption studies of the primordial IGM are a complementary probe of the reionization’s end. As we approach the reionization era from the lower redshifts, the Ly$\alpha$ forest thickens, with an occasional transmission gap due to the intersection of ionized bubbles along the line of sight (Haiman & Loeb 1999; Loeb 1999); eventually a complete GP trough is reached. The signatures of the reionization’s finale have been detected by Becker et al. (2001), Djorgovski et al. (2001), and Fan et al. (2001, 2003), in the form of extended opaque regions in the spectra of $z \geq 6$ QSOs. However, even small amounts (fraction $\sim 10^{-3}$) of the residual H I can produce the absorption troughs as those observed so far. Additional observational constraints can be obtained, e.g., from the Ly$\beta$ GP effect (Lidz et al. 2002), and the statistics of absorption window lengths as an $f(z)$ (Barkana 2002).
Figure 3. Entering the primeval forest: continuum-normalized QSO absorption spectra at progressively higher redshift windows. The forest thickens dramatically at $z \sim 5.5$ and GP-type troughs are ubiquitous at $z \geq 6$. Spectra of several high-$z$ SDSS QSOs, obtained at the Keck-II telescope with the ESI instrument were used. (From Djorgovski et al. 2002, and in prep.)

Nevertheless, there are clear indications that some qualitative change in the state of the IGM occurs at $z \sim 6$: the GP-like troughs are seen along every available line of sight to QSOs at $z > 6$; there is a change in the slope of the optical depth vs. redshift, $\tau(z)$ (Fan et al. 2002; Cen & McDonald 2002; White et al. 2003; Djorgovski et al. 2002 and in prep.; however, see Songaila & Cowie 2002 or Songaila 2004 for a contrarian view). Also, sizes of the observed H II regions around at least some $z > 6$ QSOs indicate that a substantial fraction of the IGM was neutral at this redshift (Wyithe & Loeb 2004a; Mesinger & Haiman 2004).

If both results are right – a high-$z$ reionization epoch as indicated by WMAP, and
Figure 4. The spectrum of SDSS 1148+5251, the currently most distant QSO known, at $z = 6.41$, obtained at the Keck-II telescope with the ESI instrument. The GP-type trough is evident blueward of the QSO’s Ly$\alpha$ line, as is its Ly$\beta$ counterpart (both indicated by arrows). Note also the carbon absorption doublet from a superposed galaxy at $z_{\text{abs}} = 4.9416$; its continuum emission contaminates the GP signal in this QSO spectrum, making the measurements of the optical depth difficult. (From Djorgovski et al. 2002, and in prep.)

A $z \approx 6$ reionization epoch indicated by the QSO observations, then the history of primordial star, galaxy, and AGN formation must have been very complex, possibly with multiple waves of reionization, as suggested, e.g., by Cen (2003), Wyithe & Loeb (2003b), Haiman & Holder (2003), Sokasian et al. (2004), etc.

Temporal non-uniformity and extended duration of the reionization are a natural consequence of the simple fact that the first sources of light did not all appear at the same time, having some comoving density and luminosity evolution, with the ionizing flux density gradually increasing in time (see, e.g., Umemura et al. 2001). But there might have been some spatial non-uniformity as well, if the first luminous sources were a highly biased population, as we argued above.

The inherent non-uniformities (in time and space) of galaxy and structure formation would be reflected in the structure of the reionization phase transition. In addition to the likely strong, bias-driven clustering of reionization sources (see, e.g., Barkana & Loeb 2004), key issues also include the clumpiness of the IGM (e.g., Miralda-Escudé et al. 2000), and various feedback mechanisms (see, e.g., Ferrara & Salvaterra 2004 for a review and references).

There is already some evidence for this. Current spectroscopic observations of the known QSOs at $z \sim 5.7 - 6.4$ (Djorgovski et al. 2002, and in prep.) indicate a
significant variation in the IGM transmission properties along different lines of sight. This is almost certainly a signature of a substantial bias-driven cosmic variance. There is a clear need for many more QSO lines of sight, with high-S/N, high-resolution spectra, in order to probe this effect further. A combination of the new surveys, such as Palomar-Quest (Djorgovski et al. 2004b), and further work from SDSS will provide a few tens of suitable QSOs over the next few years.

If there were such large variations in the reionization’s end and aftermath at \( z \approx 5 - 6 \), then surely there corresponding non-uniformities at higher redshifts were even greater, possibly leaving an imprint on the CMBR fluctuations (see, e.g., Santos et al. 2003). This may have some relevance for the observed excess power above the standard CDM model seen at high angular frequencies, corresponding to the comoving separations of \( \sim 10 - 20 \text{ Mpc} \) at the CMBR photosphere (Readhead et al. 2004, and references therein).
5. The First Stars and Gamma-Ray Bursts

There has been a significant progress in our understanding of primordial star formation over the past several years. A generic expectation is that the first, metal-free (Population III) stars were very massive. Unlike the star formation we know about at lower redshifts, the first stars formed without dust and metals, and probably with much less turbulence and magnetic fields, unlike their present-day counterparts.
This relative simplicity gives some hope that their formation can be understood at least in a broad-brush picture (Bromm, Coppi & Larson 1999, 2002; Abel, Bryan, & Norman 2000, 2002; etc.). The absence of heavier elements and resulting molecules which now play a major role in the protostellar cooling, implies that the predominant cooling mechanism will be through H$_2$ lines. This, along with other bits of relatively reliable physics leads to a fragmentation spectrum with a characteristic mass $M_\star \sim 10^2 - 10^4 M_\odot$ (note that the models do not yet predict an actual IMF, just a high characteristic mass). The subject of primordial star formation has been reviewed recently, e.g., by Bromm (2004).

Such supermassive stars would have typical luminosities $L \sim 10^6 - 10^7 L_\odot$ and temperatures $T_e \sim 10^5 K$, and be very effective sources of reionization photons (see, e.g., Bromm, Kudritzki, & Loeb 2001), possibly reionizing the universe at $z \sim 10 - 20$, in agreement with the WMAP results (Kogut et al. 2003). However, their radiative feedback would effectively prevent formation of any other stars in their vicinity, and their mechanical feedback may have disrupted their host protogalactic systems, possibly leading to a substantial slowdown in early star formation, and even a second recombination from a subsequent Population II stars (Cen 2003, Wyithe & Loeb 2003b). Their ejected metals would change the physics of the ISM cooling, and the subsequent formation of Population II stars may have assumed a more normal (i.e., $\sim$ present day) IMF (Bromm 2004; Yoshida et al. 2004).

It is almost certain that massive Pop.III stars would end up their lives with spectacular explosions, many of which may have resulted in a GRB (e.g., Fryer et al. 2001, Heger et al. 2002, 2003). Their explosions likely produced $\gamma$-ray bursts (GRBs), whose luminous afterglows were the brightest, if short-lived, sources in the universe at that time. Detection and studies of this putative population of primordial GRBs opens some exciting new prospects for cosmology. Cosmological uses of GRBs, including their potential as probes of the reionization era, have been reviewed, e.g., by Lamb & Reichart (2001), Loeb (2002a,b), Djorgovski et al. (2003, 2004a), Hurley et al. 2004, etc.

Progenitors in the mass range $M_\star \sim 25 - 140 M_\odot$ and $M_\star > 260 M_\odot$ would produce stellar mass black holes (BHs), and presumably GRBs; the higher mass range is especially interesting, since higher BH masses may imply higher accretion rates and thus higher GRB luminosities (the so-called Type III collapsars). In the progenitor mass range $M_\star \sim 140 - 260 M_\odot$, stars explode due to pair creation instability, leaving no remnant (and thus without a GRB).

Thus, there is some real hope that significant numbers of GRBs and their afterglows would be detectable in the redshift range $z \sim 6 - 20$, spanning the era of the first star formation and cosmic reionization (Lamb & Reichart 2001; Loeb 2002a,b; Bromm & Loeb 2002; Djorgovski et al. 2003, 2004a). This is supported by several studies in which photometric redshift indicators for GRBs suggest that a substantial fraction (ranging from $\sim 10\%$ to $\sim 50\%$) of all bursts detectable by past, current, or soon forthcoming missions may be originating at such high redshifts, even after
folding in the appropriate spacecraft/instrument selection functions (Fenimore & Ramirez-Ruiz 2000; Reichart et al. 2001; Lloyd-Ronning, Fryer, & Ramirez-Ruiz 2002; etc.). We have every reason to hope that primordial GRBs from the reionization era would be detectable with the SWIFT mission and the ground-based follow-up studies of their afterglows. The existing technology is well up to this task (Lamb & Reichart 2000, 2001; Ciardi & Loeb 2000; Gou et al. 2004).

If GRBs reflect deaths of massive stars, their very existence and statistics would provide a superb probe of the primordial massive star formation and the IMF, as well as the transition from the Pop.III to Pop.II stars. They would be by far the most luminous sources in existence at such redshifts (much brighter than SNe, and most AGN), and they may exist at redshifts where there were no luminous AGN. As such, they would provide unique new insights into the physics, evolution, and early chemical enrichment of the primordial IGM during the reionization era.

GRBs are more useful in this context than the QSOs, for several reasons. First, they may exist at high redshifts where there were no comparably luminous AGN yet. Second, their spectra are highly predictable power-laws, without complications caused by the broad Lyα lines of QSOs, and can reliably be extrapolated blueward of the Lyα line. Finally, they would provide a genuine snapshot of the intervening ISM, without an appreciable proximity effect which would inevitably complicate the interpretation of any high-z QSO spectrum: luminous QSOs excavate their Strömgren spheres in the surrounding neutral ISM out to radii of at least a few Mpc, whereas the primordial GRB hosts would have a negligible effect of that type. Finally, they may hold a key for our understanding of the origin of SMBH which power quasars.

6. The Origins of Massive Black Holes

We have discussed how there must be a deep connection between the formation of galaxies and their central SMBHs, and outlined some of the evidence which suggests that luminous QSOs at $z \sim 4 - 6$ must have started their growth and chemical enrichment at considerably higher redshifts. But where do the seed BHs of these quasars – and indeed the now ubiquitous (if quiescent) SMBHs in normal galaxies come from?

An excellent recent review of this subject is by Haiman & Quataert (2004). There are several possible physical paths towards the formation of seed BHs which grow to power quasars. First, there may be primordial BH remnants from the Big Bang; this possibility sounds a bit contrived, and we direct a curious reader to an excellent review by Carr (2003). Another possibility is a direct gravitational collapse of dark matter fluctuations, which is hard to accomplish without some high-density seeds (non-Gaussian fluctuations), and it would require that fragmentation into primordial stars is somehow avoided; while this is in principle possible, there is no evidence or even an independent need for such hypothetical scenario. There is also a possibility of a gravitational core collapse of relativistic star clusters which
may have been produced in early starbursts (see, e.g., Shapiro 2004, for a recent review and references), which might lead to a formation of BHs in a mass range $M_\bullet \sim 10^2 - 10^4 M_\odot$.

Probably the most secure astrophysical mechanism for the production of seed BHs is as remnants of massive Pop.III star explosions, producing BHs in a mass range $M_\bullet \sim 10^1 - 10^2 M_\odot$. Thus, GRBs from Pop.III stars may also represent the signal events announcing the birth of seed BHs, some or all of which eventually grow to the SMBH scales, $M_\bullet \sim 10^6 - 10^9 M_\odot$.

BHs produced by Pop.III stars can accrete material, and act as “mini-quasars” (Madau & Rees 2001; Madau et al. 2004). Their UVX emission may be a significant contributor to the early reionization, and indeed may be necessary if destructive feedback from massive Pop.III stars and their explosions was too effective (Ricotti & Ostriker 2004).

Once a seed BH is formed, it has to be grown, in some cases up to $M_\bullet \sim 10^9 M_\odot$ by $z \sim 6$. This is not a trivial task, given the limited length of time available, a few $\times 10^8$ yr (see, e.g., Haehnelt & Rees 1993). Seed BHs can grow bigger in two ways: by accretion, and by merging. Both processes are possible, and the only question is which one dominates in which range of masses, times, and environments. Models of SMBH growth within the standard hierarchical structure formation include, e.g., Haehnelt et al. (1998), Bromley et al. (2004), Volonteri et al. (2003a,b), Islam et al. (2003), Haiman (2004), Haiman et al. (2004), Yoo & Miralda Escude (2004), etc.

BH mergers open a possibility of detection of bursts of gravity waves, e.g., with the LISA mission [http://lisa.jpl.nasa.gov](http://lisa.jpl.nasa.gov).

A significant constraint on the models of SMBH growth is posed by the excellent correlations between the SMBH masses and the global dynamical properties of their host galaxies. This indicates that the growth is driven by the processes occurring on spatial scales up to nine orders of magnitude larger than the Schwarzschild radius, rather than the physics in the immediate vicinity of the BH. While it is possible that some radiative or mechanical feedback generated by the accretion machinery near the BH can affect the star formation and gas infall and outflows at larger scales, it would have to be remarkably effective, and is also unlikely to affect the dark halo masses – and yet there is an excellent correlation between the $M_\bullet$ and $M_{\text{halo}}$ (Ferrarese 2002a).

Whether the seed BHs come from the stellar/GRB remnants ($M_\bullet \sim 10-100 M_\odot$) or gravitational collapse of relativistic star clusters ($M_\bullet \sim 10^3 - 10^4 M_\odot$), an interesting question is whether there are any “intermediate” mass ($M_\bullet \sim 10^3 - 10^5 M_\odot$) still present today. A good review of this subject is given, e.g., by Miller & Colbert (2004). There are strong selection effects against detection of such objects: their masses are too small to affect stellar dynamics in galaxies at a significant level, and their accretion luminosities – if any – may be fairly low. Two possibilities have been suggested in the literature: BHs in some globular clusters (but the analysis of data which suggested this possibility has been challenged), and the so-called intermedi-
ate luminosity X-ray sources seen in the vicinity of some nearby galaxies (at least some of which turned out to be luminous background QSOs). Thus, there is at this point no conclusive evidence for the existence of intermediate mass BHs in the local universe, but this is a search well worth pursuing.

7. Concluding Comments. The Cosmic Enlightenment

Cosmology is undergoing a remarkable period of growth and discovery. Over the past decade or two, we have witnessed a number of fundamental advances in our understanding of the universe at large, and the origins and evolution of its major baryonic constituents, galaxies and LSS. Yet, it seems that we are now entering an even more exciting period, exploration of the reionization era, when the first luminous sources turned on and changed the universe.

In this short, and undoubtedly highly biased (just like the early structure formation...) review, we outlined some ways in which the luminous manifestations of BHs, from the GRBs to QSOs, can be used to illuminate crucial aspects of the early star, galaxy, and LSS formation. And while we seem to have at least some understanding of the relevant astrophysical processes and the emerging big picture of the reionization era, there are many outstanding problems and challenges.

This field will likely keep the cosmologists gainfully(?) occupied for many years to come. Just like the synergy of the HST and ground-based 8 to 10-m class telescopes changed the face of cosmology over the past dozen years, it is possible that the forthcoming space missions such as the JWST and the new generation of extremely large (20 to 60-m class) ground-based optical/IR telescopes (CELT/TMT, GMT, OWL), and large radio telescope arrays (EVLA, ALMA, LOFAR, SKA, etc.) will lead to comparable advances in our understanding of the birth of first stars, galaxies, and black holes.

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