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The First Nonlinear Structures and the Reionization History of the Universe

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Abstract

In cosmological models favored by current observations, the first astrophysical objects formed in dark matter halos at redshifts starting at $z \gtrsim 20$, and their properties were determined by primordial H_2 molecular chemistry. These protogalaxies were very abundant, but substantially less massive than typical galaxies in the local Universe. Extreme metal-poor stars, and massive black holes in their nuclei reionized the bulk of the hydrogen in the intergalactic medium. Reionization may have taken place over an extended redshift interval, ending around $z \approx 7$. Observational probes of the process of reionization may soon be afforded by studying the polarization of the cosmic microwave background anisotropies, as well as by studying the spectra and abundance of distant Lyα-emitting galaxies. Here we review theoretical expectations on how and when the first galaxies formed, and summarize future observational prospects of probing hydrogen reionization.

1.1 Introduction

Recent measurements of the cosmic microwave background (CMB) temperature anisotropies, determinations of the luminosity distance to distant Type Ia supernovae, and other observations have led to the emergence of a robust "best-fit" cosmological model with energy densities in cold dark matter (CDM) and "dark energy" of $(\Omega_{\rm m}, \Omega_\Lambda) \approx (0.3, 0.7)$ (see Bahcall et al. 1999 for a review, and references therein). The growth of density fluctuations and their evolution into nonlinear dark matter structures can be followed in this cosmological model in detail from first principles by semi-analytic methods (Press & Schechter 1974; Sheth, Mo, & Tormen 2001). More recently, it has become possible to derive accurate dark matter halo mass functions directly in large cosmological N-body simulations (Jenkins et al. 2001). Structure formation in a CDM-dominated Universe is "bottom-up," with low-mass halos condensing first. Dark matter halos with the masses of globular clusters, $10^{5-6} M_\odot$, are predicted to have condensed from $\sim 3\sigma$ peaks of the initial primordial density field as early as $\sim$1% of the current age of the Universe, or redshift $z \approx 25$.

It is natural to identify these condensations as the sites where the first astrophysical objects, such as stars, or quasars, were born. The nature of the objects that form in these early dark matter halos is currently one of the most rapidly evolving research topics in cosmology. Progress is being driven by recent observational and theoretical advances, and also by the promise of next generation instruments in several wavelength bands, such as the *James Webb Space Telescope (JWST)* in the infrared, the *Low Frequency Array (LoFAr)* in the radio, *XMM-Newton* in the X-rays, and *Laser Interferometer Space Antenna (LISA)* in gravity waves.

A comprehensive review of the status of the field two years ago was provided by Barkana & Loeb (2001); a more focused review on the role of H_2 molecules at high redshift was given by Abel & Haiman (2001). In the present paper, we briefly summarize the main theoretical issues in high-redshift structure formation, and then focus on progress in the last two years, both in theory and in observation. It is appropriate to single out* the recent discovery of a Gunn-Peterson (1965, hereafter GP) trough in the spectra of a few high-redshift quasars (Becker et al. 2001; Fan et al. 2003). The absence of any detectable flux shortward of $\sim (1+z)1216$ Å in the spectra of these $z > 6$ sources has raised the tantalizing possibility that at these redshifts we are directly probing into the epoch reionization. It has also brought into sharp focus the question of how to distinguish observationally various reionization histories. We will critically discuss these issues below.

1.2 Theoretical Expectations

1.2.1 The First Galaxy: When and How Massive?

Baryonic gas that falls into the earliest nonlinear dark matter halos is shock heated to the characteristic virial temperatures of a few hundred K. It has long been pointed out (Rees & Ostriker 1977; White & Rees 1978) that such gas needs to lose its thermal energy in order to continue contracting, or in order to fragment—in the absence of any dissipation, it would simply reach hydrostatic equilibrium, and would eventually be incorporated into a more massive halo further down the halo-merger hierarchy. While the formation of nonlinear dark matter halos can be followed from first principles, the cooling and contraction of the baryons, and the ultimate formation of stars or black holes (BHs) in these halos, is much more difficult to model *ab initio*. Nevertheless, it is useful to identify four important mass scales, which collapse at successively smaller redshifts: (1) gas contracts together with the dark matter only in dark halos above the cosmological Jeans mass, $M_{\rm J} \approx 10^4[(1+z)/11]^{3/2} M_\odot$, in which the gravity of dark matter can overwhelm thermal gas pressure; (2) gas that condensed into Jeans-unstable halos can cool and contract further in halos with masses above $M_{\rm H_2} \gtrsim 10^5[(1+z)/11]^{-3/2} M_\odot$ (virial temperatures of $T_{\rm vir} \gtrsim 10^2$ K), provided there is a sufficient abundance of H_2 molecules, with a relative number fraction at least $n_{\rm H_2}/n_{\rm H} \approx 10^{-3}$); (3) in halos with masses above $M_{\rm H} \gtrsim 10^8[(1+z)/11]^{-3/2} M_\odot$ (virial temperatures of $T_{\rm vir} \gtrsim 10^4$ K), gas can cool and contract via excitation of atomic Lyα, even in the absence of any H_2 molecules; and (4) in halos with masses above $M_{\rm H} \gtrsim 10^{10}[(1+z)/11]^{-3/2} M_\odot$ (virial temperatures of $T_{\rm vir} \gtrsim 2 \times 10^5$ K), gas can cool and contract, even in the face of an existing photoionizing background.

The first of these scales is obtained simply by balancing gravitational and pressure forces. The second scale is obtained by requiring efficient cooling via roto-vibrational levels of H_2 molecules, on a time scale shorter than the age of the Universe at the appropriate redshift. The calculations of the appropriate cooling functions for molecular hydrogen seem to be converging (Galli & Palla 1998 has done the most recent computations; see Flower et al. 2001 for a review and other references). The third scale is obtained by requiring efficient

* As this article went to press, the first results by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*; Bennett et al. 2003) experiment were announced. See the Appendix for a summary of the implications.

(Lyα line) cooling via atomic H. The fourth scale is obtained in detailed spherical collapse calculations (Thoul & Weinberg 1996).

In the earliest, chemically pristine clouds, radiative cooling is dominated by H_2 molecules. As a result, gas-phase H_2 "astro-chemistry" is likely to determine the epoch when the first astrophysical objects appear—a conclusion reached already in the pioneering works by Saslaw & Zipoy (1967) and Peebles & Dicke (1968). Several papers constructed complete gas-phase reaction networks and identified the two possible ways of gas-phase formation of H_2 via the H_2^+ or H^- channels. These were applied to derive the H_2 abundance under densities and temperatures expected in collapsing high-redshift objects (Hirasawa 1969; Matsuda, Sato, & Takeda 1969; Palla, Salpeter, & Stahler 1983; Lepp & Shull 1984; Shapiro & Kang 1987; Kang et al. 1990; Kang & Shapiro 1992; Shapiro, Giroux, & Babul 1994). Studies that incorporate H_2 chemistry into cosmological models and address issues such as nonequilibrium chemistry, dynamics, or radiative transfer, have appeared only relatively more recently. Haiman, Thoul, & Loeb (1996) and Tegmark et al. (1997) studied the masses and redshifts of the earliest objects that can collapse and cool via H_2. The first three-dimensional (3D) cosmological simulations that incorporate H_2 cooling date back to Gnedin & Ostriker (1996) and Abel et al. (1997).

The basic picture that emerged from these papers is as follows. The H_2 fraction after recombination in the smooth "protogalactic" gas is small ($x_{\rm H_2} = n_{\rm H_2}/n_{\rm H} \approx 10^{-6}$). At high redshifts ($z \gtrsim 100$), H_2 formation is inhibited even in overdense regions because the required intermediaries H_2^+ and H^- are dissociated by CMB photons. However, at lower redshifts, when the CMB energy density drops, a sufficiently large H_2 abundance builds up inside collapsed clouds ($x_{\rm H_2} \approx 10^{-3}$) at redshifts $z \lesssim 100$ to cause cooling on a time scale shorter than the dynamical time. Sufficient H_2 formation and cooling is possible only if the gas reaches temperatures in excess of ~ 200 K; or masses of few $\sim 10^5[(1+z)/11]^{-3/2} M_\odot$. The efficient gas cooling in these halos suggests that the first nonlinear object in the Universe was born inside a $\sim 10^5 M_\odot$ dark matter halo at redshift $z \approx 20$ (corresponding to a $\sim 3\sigma$ peak of the primordial density peak).

The nature of the first object is considerably more difficult to elucidate. Nevertheless, the two most natural possibilities are for stars or BHs, or perhaps both, to form. The behavior of gas in a cosmological "minihalo" is a well-defined problem that has recently been addressed in 3D numerical simulations (Abel, Bryan, & Norman 2000, 2002; Bromm, Coppi, & Larson 1999, 2002). These works have been able to follow the contraction of gas to much higher densities than previous studies. They have shown convergence toward a temperature/density regime of $T \approx 200$ K and $n \approx 10^4\,\mathrm{cm}^{-3}$, dictated by the critical density at which the excited states of H_2 reach equilibrium and cooling becomes less efficient (Galli & Palla 1998). The 3D simulations suggest that the mass of the gas fragments exceeds $10^2 - 10^3 M_\odot$, and, therefore that the first stars in the Universe may have been unusually massive (but see Nakamura & Umemura 2002, who argue using 1D and 2D simulations that the initial mass function may have been bimodal, with a second peak around $1-2 M_\odot$). An important consequence of this conclusion is that the earliest stars had an unusually hard spectrum—because they were metal free (Tumlinson & Shull 2000) and also because they were massive (Bromm, Kudritzki, & Loeb 2001), possibly capable of ionizing helium in addition to hydrogen.

1.2.2 Radiative Feedback: Negative or Positive?

The first objects will inevitably exert prompt and significant feedback on subsequent structure formation. This is because any soft UV radiation produced below 13.6 eV and/or X-rays above $\gtrsim 1$ keV from the first sources can propagate across the smooth intergalactic hydrogen gas, influencing the chemistry of distant regions (Dekel & Rees 1987). Soft UV radiation is expected either from a star or an accreting BH, with a BH possibly contributing X-rays as well. Although recent studies find that metal-free stars have unusually hard spectra, these do not extend to $\gtrsim 1$ keV (e.g., Tumlinson & Shull 2000, but see also Glover & Brandt 2003, who find stellar X-rays to have a more significant effect). The first stars formed via H_2 cooling are also expected to explode as supernovae, also producing internal feedback within or near their own parent cloud (Ferrara 1998; Omukai & Nishi 1999).

External feedback from an early soft UV background were considered by Haiman, Rees, & Loeb (1997), Haiman, Abel, & Rees (2000), Ciardi, Ferrara, & Abel (2000), and Machacek, Bryan, & Abel (2001). It was found that H_2 molecules are fragile and are universally photodissociated even by a feeble background flux (although Ricotti, Gnedin, & Shull 2002 find a positive effect: relatively near the ionizing sources, H_2 formation can be enhanced behind the H II ionization front in dense regions). H_2 dissociation by the $E < 13.6$ eV photons occurs when the UV background is several orders of magnitude lower than the value needed for cosmological reionization at $z > 5$ (and also than the level $\sim 10^{-21}\ \mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$ inferred from the proximity effect to exist at $z \approx 3$; Bajtlik, Duncan, & Ostriker 1988). The implication is a pause in the cosmic star formation history: the buildup of the UV background and the epoch of reionization are delayed until larger halos ($T_{\rm vir} \gtrsim 10^4$ K) collapse. This is somewhat similar to the pause caused later on at the hydrogen-reionization epoch, when the Jeans mass is abruptly raised from $\sim 10^4\ M_\odot$ to $\sim 10^{8-9}\ M_\odot$. An early background extending to the X-ray regime would change this conclusion, because it catalyzes the formation of H_2 molecules in dense regions (Haiman, Rees, & Loeb 1996; Haiman et al. 2000; Glover & Brandt 2003; but see also Machacek, Bryan, & Abel 2003 who find X-rays to have a less significant effect). If quasars with hard spectra ($\nu F_\nu \approx$ constant) contributed significantly to the early cosmic background radiation then the feedback might even be positive, and reionization can be caused early on by minihalos with $T_{\rm vir} < 10^4$ K.

1.2.3 The 2nd Generation: Atomic Cooling?

Whether the first sources of light were massive stars or accreting BHs (the latter termed "miniquasars" in Haiman, Madau, & Loeb 1999) is still an open question. Nevertheless, there is some tentative evidence that reionization was caused by stars, rather than quasars: high-redshift quasars appear to be rare, even at the impressive depths reached by the optical Hubble Deep Fields (Haiman et al. 1999) and the >1 Ms Chandra Deep Fields (Barger et al. 2003; see also Mushotzky et al. 2000; Alexander et al. 2001; Hasinger 2003 for earlier results on faint X-ray sources in the CDFs). There also seems to be a significant delay between the epochs of hydrogen and helium reionizations, with helium ionized only at $z \approx 3$ (Songaila 1998; Heap et al. 2000), but hydrogen already at $z > 6$ (see discussion below), implying a relatively soft ionizing background spectrum.

If indeed the first light sources were stars, without emitting a significant X-ray component above $\sim$1 keV, then efficient and widespread star (and/or BH) formation, capable of reionizing the Universe, had to await the collapse of halos with $T_{\rm vir} > 10^4$ K, or

$M_{\rm halo} > 10^8[(1+z)/11]^{-3/2} M_\odot$. The evolution of such halos differs qualitatively from their less massive counterparts (Oh & Haiman 2002). Efficient atomic line radiation allows rapid cooling to ~ 8000 K; subsequently the gas can contract to high densities nearly isothermally at this temperature. In the absence of H_2 molecules, the gas would likely settle into a locally stable disk, and only disks with unusually low spin would be unstable. However, the initial atomic line cooling leaves a large, out-of-equilibrium residual free-electron fraction (Shapiro & Kang 1987; Oh & Haiman 2002). This allows the molecular fraction to build up to a universal value of $x_{\rm H_2} \approx 10^{-3}$, almost independently of initial density and temperature (this is a nonequilibrium freeze-out value that can be understood in terms of time scale arguments; see Susa et al. 1998 and Oh & Haiman 2002).

Unlike in less massive halos, H_2 formation and cooling is much less susceptible to feedback from external UV fields. This is because the high densities that can be reached via atomic cooling. The H_2 abundance that can build up in the presence of a UV radiation field J_{21}, and hence the temperature to which the gas will cool, is controlled by the ratio J_{21}/n. For example, in order for a parcel of gas to cool down to a temperature of 500 K, this ratio has to be less than $\sim 10^{-3}$ (where J_{21} has units of $10^{-21}{\rm erg\,s^{-1}\,cm^{-2}Hz^{-1}\,sr^{-1}}$, and n has units of ${\rm cm^{-3}}$). Flux levels well below that required to fully reionize the Universe strongly suppresses the cold gas fraction in $T_{\rm vir} < 10^4$ K halos. In comparison, Oh & Haiman (2002) showed that UV radiation with the same intensity has virtually no impact on H_2 formation and cooling in $T_{\rm vir} > 10^4$ K halos, where all of the gas is able to cool to $T = 500$ K. Indeed, under realistic assumptions, the newly formed molecules in the dense disk can cool the gas to ~ 100 K, and allow the gas to fragment on scales of a few $\times 100\, M_\odot$.

Various feedback effects, such as H_2 photodissociation from internal UV fields and radiation pressure due to Lyα photon trapping, are then likely to regulate the eventual efficiency of star formation in these systems. These important questions can only be addressed with some degree of confidence by high-resolution numerical simulations that are able to track the detailed gas hydrodynamics, chemistry and cooling, paralleling the pioneering work already done for $T_{\rm vir} < 10^4$ K halos (Bromm et al. 1999; Abel et al. 2000).

Finally, it is worth noting that during the initial contraction of the gas in halos with $T_{\rm vir} > 10^4$ K a significant fraction of the cooling radiation may be emitted in the Lyα line, especially toward high redshifts, where the contracting gas has a low metallicity. The cooling radiation may be significant, and can be detectable for halos with circular velocities above $\sim 100\ {\rm km\,s^{-1}}$, as an extended, diffuse, low-surface brightness "fuzz," with an angular diameter of a few arcseconds (Haiman, Spaans, & Quataert 2000; Fardal et al. 2001). A quasar turning on during the early stages of the contraction of the gas can boost the surface brightness by a factor of ~ 100 (Haiman & Rees 2001).

1.3 Observational Prospects

1.3.1 Implications of Known High-redshift Sources

Observations over the last two years have uncovered a handful of objects at redshifts around, and exceeding, $z = 6$. Quasars discovered at $z \approx 6$ range from the very bright sources found in the Sloan Digital Sky Survey (SDSS; $M_B \approx -27.7$ mag at $5.8 \lesssim z \lesssim 6.4$; Fan et al. 2000, 2001, 2003) to the much fainter quasars found using the Keck telescope ($M_B = -22.7$ mag at $z = 5.5$; Stern et al. 2000). Galaxies around the same redshifts are being discovered via their Lyα emission lines* (Dey et al. 1998; Spinrad et al. 1998; Weymann et al. 1998; Hu, McMahon, & Cowie 1999), with some recent extreme examples ranging from star formation rates of $> 10-20 M_\odot \mathrm{yr}^{-1}$ at $z = 5.7-6.6$ (Rhoads & Malhotra 2001; Hu et al. 2002; Kodaira et al. 2003; Rhoads et al. 2003), to an exceptionally faint (with an inferred star formation rate of $0.5 M_\odot \mathrm{yr}^{-1}$) galaxy at $z = 5.56$ detected in a targeted search for gravitationally lensed and highly magnified sources behind an Abell cluster (Ellis et al. 2001).

The spatial volume that was searched to discover the various sources listed above spans ~ 9 orders of magnitude: the SDSS survey probed ~ 20 Gpc^3 to discover the bright $z \approx 6$ quasars, while the faint, strongly lensed Lyα galaxy was found in searching a mere ~ 100 Mpc^3. It is possible to associate these high-redshift sources with dark matter halos based simply on their inferred abundance: this suggests that the rare SDSS quasars reside in massive, $\sim 10^{13} M_\odot$ halos, corresponding to $4-5\sigma$ peaks in the primordial density field on these scales, while the faintest Lyα galaxies may correspond to nearly "M_*" halos with masses of $\sim 10^{10} M_\odot$. To first approximation, the existence of these objects can be naturally accommodated in the CDM structure formation models. We will next list some simple conclusions that can be drawn from the existence of the above sources.

1.3.1.1 Early Growth of Massive Black Holes

It is interesting to consider the sheer size of supermassive BHs required to power the bright SDSS quasars near $z \approx 6$. Assuming that these quasars are shining at their Eddington limit, and are not beamed or lensed*, their BH masses are inferred to be $M_\bullet \approx 4 \times 10^9 M_\odot$. The Eddington-limited growth of these supermassive BHs by gas accretion onto stellar-mass seed holes, with a radiative efficiency of $\epsilon \equiv L/\dot{m}c^2 \approx 10\%$, requires ~ 20 e-foldings on a time scale of $t_\mathrm{E} \approx 4 \times 10^7 (\epsilon/0.1)$ years. While the age of the Universe leaves just enough time ($\lesssim 10^9$ years) to accomplish this growth by redshift $z = 6$, it does mean that accretion has to start early, and the seeds for the accretion have to be present at ultra-high redshifts: $z \gtrsim 15$ or 20 for an initial seed mass of 100 or 10 $M_\odot$, respectively. This conclusion holds even when one considers that BH seeds may grow in parallel in many different early halos, which undergo subsequent mergers (Haiman & Loeb 2001). Furthermore, the radiative efficiency cannot be much higher than $\epsilon \approx 10\%$ (Haiman & Loeb 2001; Barkana, Haiman, & Ostriker 2001). Since an individual quasar BH could have accreted exceptionally fast (exceeding the Eddington limit), it will be important to apply this argument to a larger sample of high-redshift quasars. Nevertheless, we note that a comparison of the light output of quasars at the peak of their activity ($z \approx 2.5$) and the total masses of their remnant BHs at $z = 0$ (see the review by Richstone, this volume) shows that during the growth of most of the BH mass the radiative efficiency cannot be much smaller than 10%, and hence any "super-Eddington" phase must be typically restricted to building only a small fraction of the final BH mass (Yu & Tremaine 2002).

1.3.1.2 Amplification by Gravitational Lensing?

A caveat to any conclusion based on the observed fluxes of bright, distant quasars is that they may be gravitationally lensed, and strongly amplified. While the *a priori* prob-

* This type of search was proposed over 30 years ago by Partridge & Peebles (1967).
* Strong lensing or beaming would contradict the large proximity effect around these quasars; see Haiman & Cen (2002) and discussion below.

ability of strong lensing, causing amplification by a factor of > 10, along a random line of sight is known to be small ($\tau \approx 10^{-3}$) even to high redshifts (e.g., Kochanek 1998; Barkana & Loeb 2000), the *a posteriori* probabilities for observed sources can be much higher due to magnification bias (see, e.g., Schneider 1992). Magnification bias depends strongly on the parameters of the intrinsic quasar luminosity function, which are poorly constrained at $z \approx 6$. As a result, the theoretically expected probability that the SDSS quasars are strongly amplified by lensing can be significant, even approaching unity if the quasar luminosity function has an intrinsic slope steeper than -dlogΦ/dlog$L \gtrsim 4$ and/or has a break at relatively faint characteristic luminosities (Comerford, Haiman, & Schaye 2002; Wyithe & Loeb 2002a,b). As a result, observed lensed fractions can be used to provide interesting constraints on the high-redshift quasar luminosity function (Comerford et al. 2002; Fan et al. 2003).

Haiman & Cen (2002) analyzed the flux distribution of the Lyα emission of the quasar with one of the highest known redshifts, SDSS 1030+0524 at $z = 6.28$, and argued that this object could not have been magnified by lensing by more than a factor of ~ 5. The constraint arises from the large observed size, $\sim$30 (comoving) Mpc, of the ionized region around this quasar, and relies crucially only on the assumption that the quasar is embedded in a largely neutral intergalactic medium (IGM). Based on the line/continuum ratio of SDSS 1030+0524, this quasar is also unlikely to be beamed by a significant factor. The conclusion is that the minimum mass for its resident BH is $4 \times 10^8\ M_\odot$ (for magnification by a factor of 5); if the mass is this low, then the quasar had to switch on prior to redshift $z_f \gtrsim 9$. From the large size of the ionized region, an absolute lower bound on the age of this quasar also follows at $t > 2 \times 10^7$ yrs (see also the review by Martini on quasar ages in this volume).

1.3.1.3 Lyα Emitters and Cold Dark Matter

The existence of the faintest Lyα emitters may have another interesting implication. Three faint sources were found by probing a volume of only about $\sim$10 Mpc^3 (in a source plane area of $\Delta\Omega \approx 100$ arcsec^2 behind the cluster Abell 2218 and redshift range $\Delta z \approx 1$; Ellis et al. 2001). Associating the implied spatial abundance of a few $\times$ 0.1 Mpc^{-3} with those of CDM halos (Jenkins et al. 2001), these sources correspond to very low-mass ($M \approx 10^{10} M_\odot$) halos. This appears consistent with the very low star formation rates ($\sim 0.5 M_\odot \mathrm{yr}^{-1}$), inferred from the Ly$\alpha$ luminosity.

The existence of such low-mass halos is interesting from the perspective of other recent observations, which suggest that standard CDM models predict too much power for the primordial density fluctuations on small scales (see, e.g., Haiman, Barkana, & Ostriker 2001 for a brief review). Several modifications of the CDM models, exemplified by warm dark matter (WDM) models (e.g., Bode, Ostriker, & Turok 2001), have been proposed recently that reduce the small-scale power. Such modifications generally reduce the number of low-mass halos at high redshift, and if the WDM particle had a mass of $m_X \lesssim 1$ keV (or $z = 0$ velocity dispersion of $v_{\rm rms} \gtrsim 0.04$ km s^{-1}), then there may have been too few high-z sources to reionize the Universe by $z = 6$ (Barkana et al. 2001).

The faint Lyα-emitting galaxies are so far down on the mass function of halos that one can turn this into a similar constraint on the mass of the WDM particle. Indeed, for $m_X \lesssim 1$ keV, such low-mass halos would not exist at $z = 6$ (see Fig. 5 in Barkana et al. 2001). This constraint is of interest, since it is around the value of other current astrophysical limits (e.g., from the Lyα forest; Narayanan et al. 2000).

1.3.2 The Reionization History of the IGM

How and when the intergalactic plasma was reionized is one of the long-outstanding questions in astrophysical cosmology, likely holding many clues about the nature of the first generation of light sources and the end of the cosmological "Dark Age." The lack of any strong H I absorption (a GP trough) in the spectra of high-redshift quasars has revealed that the IGM is highly ionized at all redshifts $z \lesssim 6$ (Fan et al. 2000). On the other hand, the lack of a strong damping by electron scattering of the first acoustic peak in the temperature anisotropy of the CMB radiation has shown that the IGM was neutral between the redshifts $25 \lesssim z \lesssim 10^3$ (Kaplinghat et al. 2003). Together these two sets of data imply that most hydrogen atoms in the Universe were reionized during the redshift interval $6 \lesssim z \lesssim 25$.

It would be overly ambitious to provide a comprehensive review of the subject of reionization in this article. Instead, we will focus below on a few basic theoretical issues and discuss the implications of the most recent observations.

1.3.2.1 Models of Reionization

In the simplest models, an early population of stars or quasars drive expanding, discrete ionized regions. Once these regions overlap, the Universe has been reionized (e.g., Arons & Wingert 1972). In the context of CDM models, the ionizing sources form inside high-redshift dark matter halos. Since the formation and evolution of the halos is dictated by gravity alone, it is relatively well understood, and the main uncertainty in models of reionization is the "efficiency" (ionizing luminosity of stars and/or quasars) of each halo. Semi-analytical models (e.g., Shapiro et al. 1994; Tegmark, Silk, & Blanchard 1994; Haiman & Loeb 1997, 1998; Valageas & Silk 1999) and numerical simulations (Gnedin & Ostriker 1997; Nakamoto, Umemura, & Susa 2001; Gnedin 2000, 2003) adopt various, reasonably motivated, efficiencies and follow the evolution of the total volume-filling fraction of ionized regions. These models predict reionization to occur between $z = 7$ and 15, depending on the adopted efficiencies.

These studies have left significant uncertainties on the details of how reionization proceeds in an inhomogeneous medium. Since the ionizing sources are likely embedded in dense regions, one might expect that these dense regions are ionized first, before the radiation escapes to ionize the low-density IGM (Madau, Haardt, & Rees 1999; Gnedin 2000, 2003). Alternatively, most of the radiation might escape from the local, dense regions along low-column density lines of sight. In this case, the underdense "voids" are ionized first, with the ionization of the denser filaments and halos lagging behind (Miralda-Escudé, Haehnelt, & Rees 2000).

Apart from the topology of reionization, the current suite of models also leaves uncertainties about the redshift evolution of the mean ionized fraction. Most models predict a sharp increase whenever the discrete ionized regions percolate. However, if the formation rate of the ionizing sources does not parallel the collapse of high-σ peaks, reionization can be more gradual, and can have a complex history. For instance, the radiative H_2 feedback discussed above may result in two distinct episodes of reionization: (1) UV sources formed via H_2 cooling in minihalos partially ionize the Universe at $z \approx 20$, (2) the IGM recombines as these sources turn off, and (3) the Universe is reionized at $z \approx 7$ by UV sources in more massive halos. The first episode of reionization may be more pronounced, since the metal-free stars in minihalos are expected to have an unusually high ionizing photon production efficiency (see also Wyithe & Loeb 2003a; Cen 2003a).

Depending on the choice of the efficiency parameters, it is also possible that the IGM only partially recombines during stage (2), resulting in an extended episode of partial ionization (Cen 2003a). Finally, the decrease of the mean neutral fraction would be more gradual if the ionizing sources had a hard spectrum. Reionization by X-rays was considered recently by Oh (2001) and Venkatesan, Giroux, & Shull (2001). In contrast to a picture in which discrete H II regions eventually overlap, in this case the IGM is ionized uniformly and gradually throughout space. All of these uncertainties highlight the need for new and sensitive observational probes of the reionization history, which we will discuss in the next section.

A significant source of theoretical uncertainty in the above models is the average global recombination rate, or "clumping factor," which limits the growth of H II regions at high redshifts, when the Universe was dense. Although hydrodynamical simulations can compute gas clumping *ab initio* (Gnedin & Ostriker 1997), to date they have not been able to resolve the relevant small scales (the minihalos have typical masses below $10^7 M_\odot$). Gas clumping has been estimated semi-analytically (Chiu & Ostriker 2000; Benson et al. 2001; Haiman, Abel, & Madau 2001). In particular, Haiman et al. (2001) pointed out that the earliest ionizing sources are likely surrounded by numerous "minihalos" that had collapsed earlier, but had failed to cool and form any stars or quasars. The mean-free path of ionizing photons, before they are absorbed by a minihalo*, is about ~ 1 (comoving) Mpc. Simple models, summing over the expected population of minihalos, reveal that on average an H atom in the Universe recombines $\gtrsim 10$ times before redshift $z = 6$; as a result, the IGM had to be "reionized $\gtrsim 10$ times."

A naive extrapolation of the luminosity density of bright quasars toward $z = 6$ reveals that these sources fall short of this requirement (Haiman et al. 2001; see also Shapiro et al. 1994). Extrapolating the known population of Lyman-break galaxies (e.g., Steidel, Pettini, & Adelberger 2001) toward $z = 6$ comes closer: assuming that 15% of the ionizing radiation from Lyman-break galaxies escapes into the IGM (on average, relative to the escape fraction at 1500 Å), a naive extrapolation shows that Lyman-break galaxies emitted approximately one ionizing photon per hydrogen atom prior to $z = 6$. The implication is that the ionizing emissivity at $z > 6$ was ~ 10 times higher than provided by a straightforward extrapolation back in time of known quasar and galaxy populations. The Universe was likely reionized by a population of UV sources that is yet to be discovered!

1.3.2.2 Current Observations

The recent discovery of the bright quasar SDSS 1030+0524 in the SDSS at redshift $z = 6.28$ has, for the first time, revealed a full GP trough, i.e., a spectrum consistent with no flux at high S/N over a substantial stretch of wavelength shortward of $(1+z)\lambda_\alpha = 8850$ Å (Becker et al. 2001). At the time of this writing, a full GP trough has been discovered at high S/N in a second SDSS quasar at $z = 6.43$, and at a lower S/N in two other SDSS quasars (at $z = 6.23$ and $z = 6.05$; Fan et al. 2003; an "incomplete" trough was also reported at high S/N in a $z = 5.7$ source by Djorgovski et al. 2001).

These discoveries have raised the tantalizing possibility that we are detecting reionization occurring near redshift $z \approx 6.3$. The lack of any detectable flux indeed implies a strong lower limit, $x_{\rm H} \gtrsim 0.01$, on the mean mass-weighted neutral fraction of the IGM at $z \approx 6$ (Cen & McDonald 2002; Fan et al. 2002; Lidz et al. 2002; Pentericci et al. 2002). Still, the

* Photoionization unbinds the gas in these shallow potential wells (Shapiro, Raga, & Mellema 1998; Barkana & Loeb 1999). The gas acts as a sink of ionizing photons only before it is photoevaporated.

evolution of the IGM opacity inferred from quasar spectra does not directly reveal whether we have probed the neutral era. Nevertheless, comparisons with numerical simulations of cosmological reionization (Cen & McDonald 2002; Fan et al. 2002; Gnedin 2003; Lidz et al. 2002; Razoumov et al. 2002), together with the rapid rise toward high redshifts of the neutral fractions inferred from a sample of high-redshift quasars from $5.5 \lesssim z \lesssim 6$ (Songaila & Cowie 2002), suggest that the IGM is likely neutral at $z \gtrsim 6.5$.

While there may be a theoretical bias for reionization occurring close to $z \approx 6.3$, it is possible that the reionization history was nonmonotonic, and/or lasted over a considerably longer redshift interval, as was discussed above. An observational probe of the redshift history of reionization would be invaluable in constraining such scenarios, and to securely establish when the cosmic Dark Age ended. Below we consider prospects to probe the reionization history in future observations. Another interesting issue (not discussed further below) raised by the recent GP trough detections is: What is the best way to interpret quasar spectra? Using simply the wavelength extent of the "dark" region (without any detectable flux) in the spectrum is not, by itself, generally sufficient to give a strong constraint on the global topology of neutral versus ionized regions, because of stochastic variations. Other statistical measures need to be developed (Barkana 2002; Lidz et al. 2002; Nusser et al. 2002).

1.3.2.3 Future Probes of Reionization

CMB Polarization. An alternative way of probing deeper into the dark ages is the study of CMB anisotropies: the free electrons produced by reionization scatter a few percent of the CMB photons. Interesting results may be imminent from the ongoing CMB satellite experiment *WMAP*. The discussion below is based largely on the results of Kaplinghat et al. (2003); for a detailed review, see Haiman & Knox (1999).

Without reionization, the "primordial" polarization signal at large angles would be negligible. However, CMB photons scattering in a reionized medium boost the polarization signal—likely making it measurable in the future. CMB polarization anisotropy at large angles is very sensitive to the optical depth to electron scattering, and the future experiment *Planck* (and if the optical depth is large, then *WMAP* as well), will have the power to discriminate between different reionization histories even when they lead to the same optical depth.

One of the advantages of studying the CMB is that it probes the presence of free electrons, and can therefore detect a neutral hydrogen fraction of $x_{\rm H} = 0.1$ and $x_{\rm H} = 10^{-3}$ with nearly equal sensitivity. Physically, the CMB and the GP trough therefore probe two different stages of reionization. The CMB is sensitive to the initial phase when $x_{\rm H}$ first decreases below unity and free electrons appear, say, at redshift z_e. On the other hand, the (hydrogen) GP trough is sensitive to the end phase, when neutral hydrogen atoms finally disappear, say, at $z_{\rm H}$. In most models, these two phases coincide to $\lesssim 10\%$ of the Hubble time, such that $z_e \approx z_{\rm H}$. However, as argued above, one can conceive alternative theories in which the two phases are separated by a large redshift interval, and $z_e \gg z_{\rm H}$.

One of the difficulties with CMB is that the effect of electron scattering on the temperature anisotropies is essentially an overall suppression, nearly degenerate with the intrinsic amplitude of the fluctuation power spectrum. However, Kaplinghat et al. (2003) showed that for most models constrained by current CMB data and by the discovery of a GP trough (i.e., requiring that reionization occurred at $z > 6.3$), *WMAP* can break this degeneracy, and detect the reionization signature in the polarization power spectrum.* The expected 1σ error on the measurement of the electron optical depth is around $\delta\tau \approx 0.03$, with only a weak dependence on the actual value of τ. This will also allow *WMAP* to achieve a 1σ error on the amplitude of the primordial power spectrum of 6%. As an example, *WMAP* with two years (*Planck* with one year) of observation can distinguish a model with 50% (6%) partial ionization between redshifts of 6.3 and 20 from a model in which hydrogen was completely neutral at redshifts greater than 6.3. *Planck* will be able to distinguish between different reionization histories even when they imply the same optical depth to electron scattering for the CMB photons (Holder et al. 2003; Kaplinghat et al. 2003).

Lyα Emitters. An alternative method to probe the reionization history is to utilize the systematic changes in the profiles of Lyα emission lines toward higher redshift. The increased hydrogen IGM opacity beyond the reionization redshift makes the emission lines appear systematically more asymmetric, and the apparent line center systematically shifts toward longer wavelengths, as absorption in the IGM becomes increasingly more important and eliminates the blue side of the line (Haiman 2002; Madau 2003). Because of the intrinsically noisy Lyα line shapes, this method will require a survey that delivers a large sample of Lyα emitters (Rhoads et al. 2002).

Lyα photons injected into a neutral IGM are strongly scattered, and the red damping wing of the GP trough can strongly suppress, or even completely eliminate, the Lyα emission line (Miralda-Escudé 1998; Miralda-Escudé & Rees 1998; Loeb & Rybicki 1999). Resonant absorption by the IGM may itself extend to the red side of the line, if there is still significant cosmological gas infall toward the source (Barkana & Loeb 2003). The reionization of the IGM may therefore be accompanied by a rapid decline in the observed space density of Lyα emitters beyond the reionization redshift z_r (Haiman & Spaans 1999). Indeed, such a decline could by itself provide a useful observational probe of the reionization epoch in a large enough sample of Lyα emitters (Haiman & Spaans 1999; Rhoads & Malhotra 2001), complementary to methods utilizing the GP trough.

As shown by Cen & Haiman (2000) and Madau & Rees (2000), a source with a bright ionizing continuum can create a large ($\gtrsim 30$ comoving Mpc) cosmological H II region. For a sufficiently luminous source, and/or for a sufficiently wide intrinsic Lyα line width, the size of the H II region corresponds to a wavelength range $\Delta\lambda$ that exceeds the width of the emission line, allowing most of the intrinsic Lyα line to be transmitted without significant scattering. Furthermore, even for faint sources with little ionizing continuum, a significant fraction of the emission line can remain observable if the intrinsic line width is $\Delta v \gtrsim 300$ km s^{-1} (Haiman 2002).

The recent discovery of Lyα-emitting galaxies with the Keck and Subaru telescopes at redshifts as high as $z = 6.56$ (Hu et al. 2002) and $z = 6.58$ (Kodaira et al. 2003) illustrates the fact the Lyα lines can indeed be detected even at these high redshifts. These redshifts exceed those at which the GP troughs were discovered in the SDSS quasar spectra, and hence these galaxies could be located *beyond* the reionization redshift of the IGM. The Hu et al. spectrum is consistent with being embedded in a neutral IGM that only partially obscures the line, and

* A detailed morphological study of the effects of reionization on maps of the temperature anisotropy may also be helpful to break this degeneracy (Gnedin & Shandarin 2002).

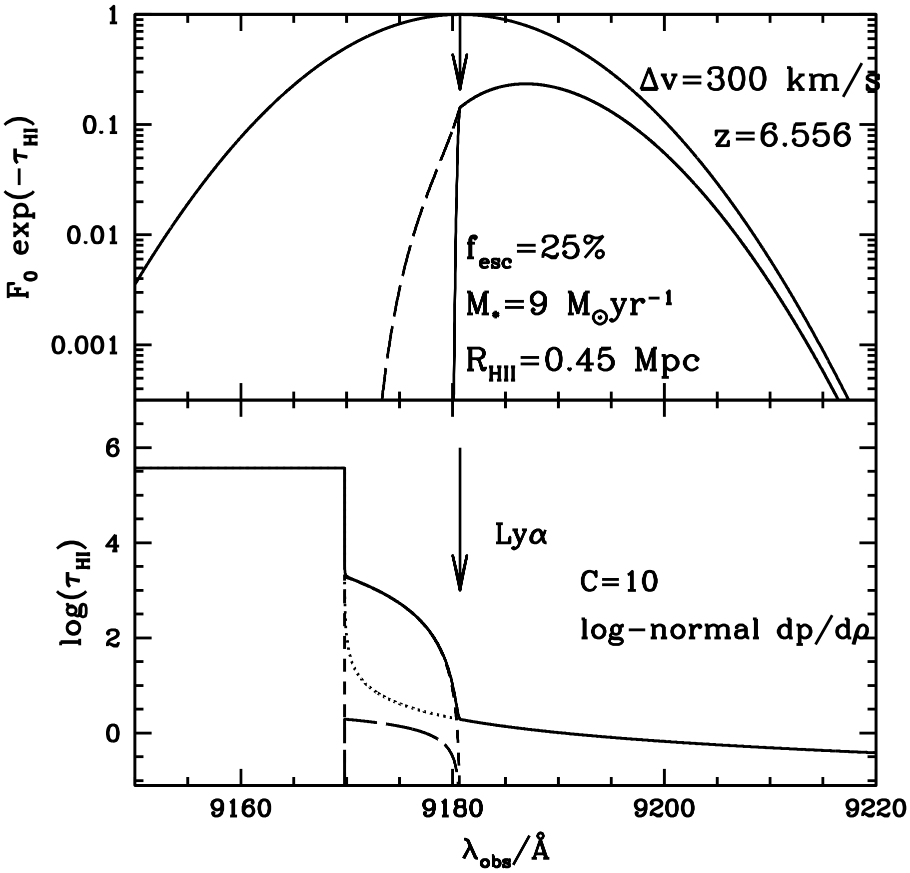

Fig. 1.1. *Upper panel:* Toy model profile of the Lyα line from a $z = 6.56$ galaxy. The top solid curve shows the adopted intrinsic profile, and the bottom solid curve shows the profile including absorption in the IGM and by the neutral atoms inside the 0.45 (proper) Mpc H II region surrounding the source. *Lower panel:* The optical depth as a function of wavelength from within the H II region (short-dashed curve), from the neutral IGM outside the H II region (dotted curve), as well as from the sum of the two (solid curve). In both panels, the long-dashed curves describe an alternative, more realistic treatment of the H I opacity within the H II region (see Haiman 2002 for a discussion), and the arrows indicate the central wavelength of the unobscured Lyα line.

allows $\sim 20\%$ of the total line flux to be transmitted (Haiman 2002; see Fig. 1.1). This would imply that the source is somewhat surprisingly bright, given the inferred abundance and estimates of the number density of $z \approx 5.7$ Lyα emitters from a different survey (Rhoads et al. 2003).

Although the lines are detectable, the IGM still has a significant effect on the Lyα line profile. A statistical sample of Lyα emitters that spans the reionization redshift should be a useful probe of reionization, through the study of the correlations between the luminosity of the sources and the properties of the emission lines, such as their total line/continuum ratio (if a continuum is measured), the asymmetry of the line profile, and the offset of the peak of the line from the central Lyα wavelength (for sources that have redshift measurements from other emission lines).

Redshifted 21 cm Features. Future radio telescopes could observe 21 cm emission or absorption from neutral hydrogen at the time of reionization (see a recent review by Madau 2004). This would provide a direct measure of the physical state of the neutral hydrogen and its evolution through the time of reionization. Recently, Carilli, Gnedin, & Owen (2002) considered the radio equivalent of the GP trough, using numerical simulations. Unlike the Lyα case, the mean absorption by the neutral medium is about 1% at the redshifted 21 cm. Furlanetto & Loeb (2002) and Iliev et al. (2002) have used semi-analytic methods to look at the observable features (in 21 cm) of minihalos and protogalactic disks. These studies suggest that the 21 cm observations would yield robust information about the thermal history of collapsed structures and the ionizing background, provided that a sufficiently bright radio-loud quasar can be found at $z_e > 6.3$. In addition, characteristic angular fluctuations that trace early density fluctuations of the 21-cm emitting gas (e.g., Madau, Meiksin, & Rees 1997; Tozzi et al. 2000) may be detectable in the future.

Gunn-Peterson Trough in Metal Lines. Although detections of the hydrogen GP trough suffer from the "saturation problem" discussed above, an alternative possibility may be to use corresponding absorption troughs caused by heavy elements in the high-redshift IGM. Recently, Oh (2002) showed that if the IGM is uniformly enriched by metals to a level of $Z = 10^{-2} - 10^{-3}\ Z_{\odot}$, then absorption by resonant lines of O I or Si II may be detectable. The success of this method depends on the presence of oxygen and silicon at these levels, and on these species being neutral or once-ionized in regions where hydrogen has not yet been ionized. It may be more natural for hydrogen reionization to precede metal enrichment, rather than vice versa, however; because of the short recombination time at high redshift, the gas can remain neutral even in the metal-enriched regions, and may provide the absorption features necessary for its detection.

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Appendix: Implications of First WMAP Results

As this article went to press, the first results by the *WMAP* experiment were announced. These new results have significant implications for reionization, which we only briefly summarize here. *WMAP* has measured the optical depth to electron scattering from the cross-correlation between the the temperature and E-mode polarization angular power spectra (TE; Spergel et al. 2003), yielding the high value of $\tau = 0.17 \pm 0.06$. The value reflects marginalization over all other relevant cosmological parameters. A reassuringly similar value, $\tau = 0.17 \pm 0.04$, is obtained by predicting the TE power spectrum directly from the temperature power spectrum (Kogut et al. 2003).

The immediate conclusion that can be drawn from the high value of τ is that the IGM was significantly ionized at redshifts as early as $z \approx 15$. This discovery has important implications for the sources of reionization, and allows, for the first time, constraints to be placed on physical reionization scenarios out to redshift $z \approx 20$. The *WMAP* results have been interpreted by a flurry of papers presenting models of the reionization history in the few weeks following the data release (Cen 2003b; Ciardi, Ferrara, & White 2003; Fukugita & Kawasaki 2003; Haiman & Holder 2003; Sokasian, Abel, & Hernquist 2003; Somerville & Livio 2003; Wyithe & Loeb 2003b). The reader is referred to these papers for many interesting details; no doubt the list of papers devoted to reionization will continue to grow by the time this article appears in print.

The main implications of the *WMAP* result can be summarized as follows (based on Haiman & Holder 2003, but broadly consistent with the conclusions reached in all the interpretive papers listed above).

• Previous evidence has shown that the IGM is highly ionized at least out to redshift $z \approx 6$. As argued in the body of this article, there is also evidence that a "percolation epoch" is taking place near $z \approx 6-7$.* Abrupt reionization at $z = 6$ would yield $\tau \approx 0.04$, significantly lower than the *WMAP* value.

• Reionization models predict a "percolation" redshift that depends on the combination of efficiency parameters, essentially on $\epsilon \equiv N_\gamma f_* f_{\rm esc}/C$, where $f_* \equiv M_*/(\Omega_{\rm b} M_{\rm halo}/\Omega_{\rm m})$ is the fraction of baryons in the halo that turns into stars; N_γ is the mean number of ionizing photons produced by an atom cycled through stars, averaged over the initial mass function of the stars; $f_{\rm esc}$ is the fraction of these ionizing photons that escapes into the IGM; and C is the mean clumping factor of ionized gas. A value of $\epsilon \approx 10$ is required for percolation to occur at $z \approx 6$. This value is quite reasonable, and it produces a natural "tail" of ionization at redshifts exceeding $z = 6$ in these models (due to the gradual turn-on of ionizing sources associated with dark halos; see Figure 1.2). This "tail" increases the optical depth to $\tau \approx 0.08$, which is still discrepant with the *WMAP* value at the $\sim 3\sigma$ level.

• As a result, no simple reionization model can be consistent with the combination of the central *WMAP* value of $\tau = 0.17$ *and* a percolation occurring at $z \approx 6$. Satisfying both constraints requires either of the following: (1) H_2 molecules form efficiently at $z \approx 20$, survive feedback processes, and allow UV sources in halos with virial temperatures $T_{\rm vir} < 10^4$ K to contribute substantially to reionization, or (2) the efficiency ϵ in halos with $T_{\rm vir} > 10^4$ K decreased by a factor of $\gtrsim 30$ between $z \approx 20$ and $z \approx 6$. The latter may be a natural result of a switch-over from a metal-free to a normal stellar population (Wyithe & Loeb 2003a; Cen 2003a). These options are illustrated by the upper three curves in Figure 1.2.

• As apparent from above, there are interesting implications for the formation history of ionizing sources, but there is no "crisis" for cosmology: ΛCDM cosmogonies can still accommodate the high value of τ measured by *WMAP*. However, interesting limits can be drawn on cosmological models with reduced small-scale power. As an example, the combination of *WMAP* and other large-scale structure data has provided tentative evidence for a running

* Hui & Haiman (2003) have argued that there is additional evidence for percolation at $z < 10$ from the *thermal* history of the IGM.

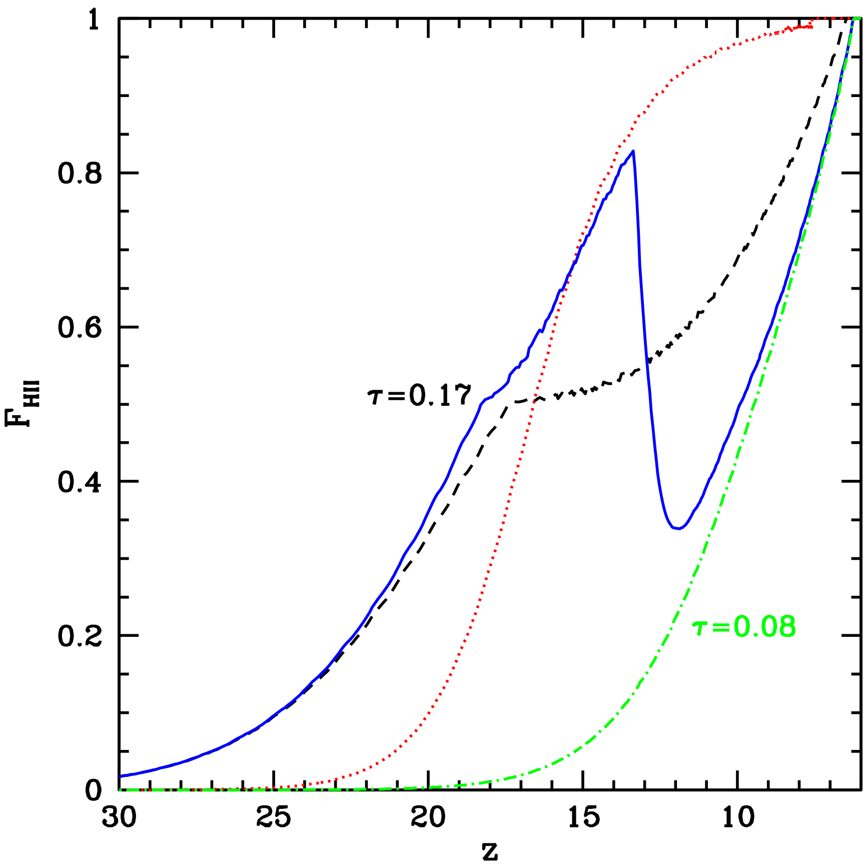

Fig. 1.2. Model reionization histories (evolution of ionized fraction with redshift). The dot–dashed curve is a simple model with "universal" efficiencies calibrated to produce reionization at $z = 6$. It produces a low optical depth of $\tau = 0.08$. The other three models satisfy the dual requirement of (1) a low–redshift ($z \sim 6$) percolation epoch, and a (2) high value of electron scattering optical depth ($\tau \sim 0.17$) by (1) increased efficiency in "mini–halos" (solid curve), (2) excluding minihalos, but increasing the efficiencies in larger halos (dotted curve), and (3) a sudden drop in efficiencies, (e.g. due to a transition from metal-free to normal stellar population). The three models produce large–angle polarization signatures in the CMB that will be distinguishable by Planck. (Adapted from Haiman & Holder 2003).

spectral index in the power spectrum $P(k)$. Haiman & Holder (2003) and Somerville et al. (2003) have shown that in the favored running-index model achieving $\tau = 0.17$ is impossible without extreme efficiencies of ionizing photon production in halos with virial temperatures $T_{\rm vir} < 10^4$ K; a significantly stronger curvatures could be ruled out. Similar conclusions can be drawn (Somerville, Bullock, & Livio 2003) about models with a strong tilt in the scalar power-law index n, or about WDM models (see also Barkana et al. 2001 and Yoshida et al. 2003 for limits even on "lukewarm" dark matter models from reionization at $z \approx 20$.)

It is also worth emphasizing that the reionization history is likely to have been complex enough so that it will have distinctive features that *Planck* can distinguish at $> 3\sigma$ significance (see Fig. 1.2; and also Holder et al. 2003). At the high *WMAP* value for τ, *Planck* will be able to provide tight statistical constraints on reionization model parameters and help elucidate the nature of the sources ending the Dark Ages. In addition to the large-angle polarization signatures from reionization, small-scale fluctuations in the IGM temperature may be observable (a "Sunyaev-Zel'dovich" effect from high-redshift ionized regions; Oh, Cooray, & Kamionkowski 2003). Finally, the sources responsible for the high optical depth discovered by *WMAP* should be directly detectable out to $z \approx 15$ by the *JWST*.

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