The Growth of the Earliest Supermassive Black Holes and Their Contribution to Reionization

Zoltán Haiman, Mark Dijkstra, and Andrei Mesinger

Department of Astronomy, Columbia University, New York, NY 10027, USA

Abstract. We discuss currently available observational constraints on the reionization history of the intergalactic medium (IGM), and the extent to which accreting black holes (BHs) can help explain these observations. We show new evidence, based on the combined statistics of Lyman $\alpha$ and $\beta$ absorption in quasar spectra, that the IGM contains a significant amount of neutral hydrogen, and is experiencing rapid ionization at redshift $z \sim 6$. However, we argue that quasar BHs, even faint ones that are below the detection thresholds of existing optical surveys, are unlikely to drive the evolution of the neutral fraction around this epoch, because they would over-produce the present-day soft X-ray background. On the other hand, the seeds of the $z \sim 6$ quasar BHs likely appeared at much earlier epochs ($z \sim 20$), and produced hard ionizing radiation by accretion. These early BHs are promising candidates to account for the high redshift ($z \sim 15$) ionization implied by the recent cosmic microwave anisotropy data from WMAP. Using a model for the growth of BHs by accretion and mergers in a hierarchical cosmology, we suggest that the early growth of quasars must include a super-Eddington growth phase, and that, although not yet optically identified, the FIRST radio survey may have already detected several thousand $>10^8 M_\odot$ BHs at $z > 6$.

1 Black Holes and Reionization

The recent discovery of the Gunn–Peterson (GP) troughs in the spectra of $z > 6$ quasars in the Sloan Digital Sky Survey (SDSS) [5,12,51], has suggested that the end of the reionization process occurs at a redshift near $z \sim 6$. On the other hand, the high electron scattering optical depth, $\tau_e = 0.17 \pm 0.04$, measured recently by the Wilkinson Microwave Anisotropy Probe (WMAP) experiment [46] suggests that ionizing sources were abundant at a much higher redshift, $z \sim 15$. These data imply that the reionization process is extended and complex, and is probably driven by more than one population of ionizing sources (see, e.g., [16] for a recent review).

The exact nature of the ionizing sources remains unknown. Natural candidates to account for the onset of reionization at $z \sim 15$ are massive, metal-free stars that form in the shallow potential wells of the first collapsed dark matter halos [52,6,20]. The completion of reionization at $z \sim 6$ could then be accounted for by a normal population of less massive stars that form from the metal–enriched gas in more massive dark matter halos present at $z \sim 6$.

The most natural alternative cause for reionization is the ionizing radiation produced by gas accretion onto an early population of black holes (“mini-quasars”; [21]). The ionizing emissivity of the known population of quasars di-
minishes rapidly beyond $z \gtrsim 3$, and bright quasars are unlikely to contribute significantly to the ionizing background at $z \gtrsim 5$ [44,18]. However, if low–luminosity, yet undetected miniquasars are present in large numbers, they could dominate the total ionizing background at $z \sim 6$ [21]. Recent work, motivated by the WMAP results, has emphasized the potential significant contribution to the ionizing background at the earliest epochs ($z \sim 15$) from accretion onto the seeds of would-be supermassive black holes [32,41]. The soft X–rays emitted by these sources can partially ionize the IGM early on [39,48].

In this contribution, we address the following issues: (1) What is the fraction of neutral hydrogen in the IGM at $z \sim 6$? (2) Can quasar black holes contribute to reionization either at $z \sim 6$ or at $z \sim 15$? (3) How did BHs grow, in a cosmological context, starting from early, stellar–mass seeds at $z \sim 20$? (4) Can we detect massive early ($z > 6$) black holes directly? Numerical statements throughout this paper assume a background cosmology with parameters $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_b = 0.044$, and $h = 0.71$, consistent with the recent measurements by WMAP [46].

2 What is the Neutral Fraction of Hydrogen at $z \sim 6$?

The ionization state of the IGM at redshift $6 \lesssim z \lesssim 7$ has been a subject of intense study over the past few years. While the WMAP results imply that the IGM is significantly ionized out to $z \sim 15$, several pieces of evidence suggest that it has a high neutral fraction at $z \sim 6 - 7$.

One argument against a simple model, in which the IGM is ionized at $z \sim 15$, and stays ionized thereafter, comes from the thermal history of the IGM [27,47]. The temperature of the IGM, measured from the Ly$\alpha$ forest, is quite high at $z \sim 4$, with various groups finding values around $T \sim 20,000K$ [56,34,43]. As long as the universe is reionized before $z = 10$ and remains highly ionized thereafter, the IGM reaches an asymptotic thermal state, determined by a competition between photoionization heating and adiabatic cooling (the latter being due to the expansion of the universe). Under reasonable assumptions about the ionizing spectrum, the IGM then becomes too cold at $z = 4$ compared to observations [27]. Therefore, there must have been significant (order unity) changes in fractions of neutral hydrogen and/or helium at $6 < z < 10$, and/or singly ionized helium at $4 < z < 10$. An important caveat to this argument is the possible existence of an additional heating mechanism that could raise the IGM temperature at $z \sim 4$. Galactic outflows could heat the IGM, in principle, but observations of close pairs of lines of sight in lens systems suggest that the IGM is not turbulent on small-scales, arguing against significant stir–up of the IGM by winds [40]. The known quasar population is likely driving the reionization of helium, HeII$\rightarrow$HeIII, at $z \sim 3$ (e.g. [26]). If this process starts sufficiently early, i.e. at $z \gtrsim 4$, then HeII photoionization heating could explain the high IGM temperature. It would be interesting to extend the search for HeII patches that do not correlate with HI absorption to $z \sim 4$ to test this hypothesis.
A second argument for a large neutral fraction comes from the rapid redshift–evolution of the transmission near the redshifted Ly\(\alpha\) wavelength in the spectra of distant quasars. The Sloan Digital Sky Survey (SDSS) has detected large regions with no observable flux in the spectra of several \(z \sim 6\) quasars \([5,12,51]\). The presence of these Gunn-Peterson (GP) troughs by itself only sets a lower limit on the volume weighted hydrogen neutral fraction of \(x_{\text{HI}} \gtrsim 10^{-3}\) \([11]\). However, this strong limit implies a rapid evolution in the ionizing background, by nearly an order of magnitude in amplitude, from \(z = 5.5\) to \(z \sim 6\) \([8,11,30]\) (we note that the Lyman \(\beta\) region of the spectra, which is needed for this conclusion, is dismissed in another recent study \([45]\), which therefore reaches different conclusions). Known ionizing populations (quasars and Lyman break galaxies) do not evolve this rapidly; comparisons with numerical simulations of cosmological reionization (e.g. \([15]\)) suggests that we are, instead, witnessing the end of the reionization epoch, with the IGM becoming close to fully neutral at \(z \sim 7\). At this epoch, when discrete HII bubbles percolate, the mean–free–path of ionizing photons can evolve very rapidly (e.g. \([22]\)) and could explain the steep evolution of the background flux.

However, perhaps the strongest argument for a large neutral fraction comes from the presence of the cosmic Strömgren spheres surrounding high–\(z\) quasars. If indeed the intergalactic hydrogen is largely neutral at \(z \sim 6\), then quasars at this redshift should be surrounded by large ionized (HII) regions, which will strongly modify their absorption spectra \([31,7]\). Recent work has shown that the damping wing of absorption by neutral hydrogen outside the HII region imprints a feature that is statistically measurable in a sample of \(\sim 10\) bright quasars without any additional assumptions \([38]\). A single quasar spectrum suffices if the size of the Strömgren sphere is constrained independently \([38,37]\). In addition, with a modest restriction (lower limit) on the age of the source, the size of the HII region itself can be used to place stringent limits on the neutral fraction of the ambient IGM \([54]\).

To elaborate on these last arguments, based on the quasar’s HII region, in Figure 1 we illustrate a model for the optical depth to Lyman \(\alpha\) absorption as a function of wavelength towards a \(z_{\text{Q}} = 6.28\) quasar, embedded in a neutral medium \((x_{\text{HI}} = 1)\), but surrounded by a Strömgren sphere with a comoving radius of \(R_{\text{S}} = 44\) Mpc. Around bright quasars, such as those recently discovered \([10,12]\) at \(z \sim 6\), the proper radius of such Strömgren spheres is expected to be \(R_{\text{S}} \approx 7.7 \times 10^{-1/3} (N_{\text{Q}}/6.5 \times 10^{57}\text{ s}^{-1})^{1/3} (t_{\text{Q}}/2 \times 10^7\text{ yr})^{1/3} [(1+z_{\text{Q}})/7.28]^{-1}\) Mpc \([31,7]\). Here \(x_{\text{HI}}\) is the volume averaged neutral fraction of hydrogen outside the Strömgren sphere and \(N_{\text{Q}}, t_{\text{Q}}\), and \(z_{\text{Q}}\) are the quasar’s production rate of ionizing photons, age, and redshift. The fiducial values are those estimated for the \(z = 6.28\) quasar J1030+0524 \([19,54]\). The mock spectrum shown in Figure 1 was created by computing the Lyman \(\alpha\) opacity from a hydrodynamical simulation (kindly provided by R. Cen; the analysis procedure is described in \([37]\)). The optical depth at a given observed wavelength, \(\tau_{\text{obs}}\), can be written as the sum of contributions from inside \((\tau_{R})\) and outside \((\tau_{D})\) the Strömgren sphere, \(\tau_{\text{obs}} = \tau_{R} + \tau_{D}\). The residual neutral hydrogen inside the Strömgren sphere at redshift
Fig. 1. Model from a hydrodynamical simulation for the optical depth contributions from within ($\tau_R$) and from outside ($\tau_D$) the local ionized region for a typical line of sight towards a $z_Q = 6.28$ quasar embedded in a fully neutral, smooth IGM, but surrounded by a local HII region of (comoving) radius $R_S = 44$ Mpc. The dashed curve corresponds to $\tau_D$, and the solid curve corresponds to $\tau_R$. The total Lyman $\alpha$ optical depth is the sum of these two contributions, $\tau_{Ly\alpha} = \tau_R + \tau_D$. The dashed-dotted lines demarcate the three wavelength regions used for our analysis described in the text. For reference, the redshifted Lyman $\alpha$ wavelength is at $8852 \AA$, far to the right off the plot.

$z < z_Q$ resonantly attenuates the quasar’s flux at wavelengths around $\lambda_{Ly\alpha}(1+z)$, where $\lambda_{Ly\alpha} = 1215.67 \AA$ is the rest-frame wavelength of the Lyman $\alpha$ line center. As a result, $\tau_R$ is a fluctuating function of wavelength (solid curve), reflecting the density fluctuations in the surrounding gas. In contrast, the damping wing of the absorption, $\tau_D$, is a smooth function (dashed curve), because its value is averaged over many density fluctuations. As the figure shows, the damping wing of the absorption from the neutral universe extends into wavelengths $\lambda_{obs} \gtrsim 8720 \AA$, and can add significantly to the total optical depth in this region.

The sharp rise in $\tau_D$ at wavelengths $\lambda_{obs} \lesssim 8720 \AA$ is a unique feature of the boundary of the HII region, and corresponds to absorption of photons redshifting into resonance outside of the Strömgren sphere. The detection of this feature has been regarded as challenging: since the quasar’s flux is attenuated by a factor of $\exp(-\tau_{Ly\alpha})$, an exceedingly large dynamical range is required.
Fig. 2. The Keck ESI spectrum of the $z = 6.28$ quasar SDSS J1030+0524 [51], in units of $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, and including uncorrelated $1\sigma$ errors. The upper and lower panels show the regions of the spectrum corresponding to Lyman $\alpha$ and $\beta$ absorption in the redshift range $6.15 < z < 6.28$. The Lyman $\beta$ cross section is smaller than Lyman $\alpha$, and a significantly higher column of neutral hydrogen is required to block the flux in the Lyman $\beta$ region than in the Lyman $\alpha$ region. This spectrum therefore requires a steep increase in the opacity over the narrow range from $z = 6.20$ to $z = 6.16$, explainable only by a GP damping wing, as shown by the dashed curve in Figure 1.

In the corresponding flux measurements. However, simultaneously considering the measured absorption in two or more hydrogen Lyman lines can provide the dynamical range required to detect this feature [37].

In particular, we modeled broad features of the Lyman $\alpha$ and Lyman $\beta$ regions of the absorption spectrum of the $z = 6.28$ quasar SDSS J1030+0524. The observational input to our analysis is the deepest available absorption spectrum of SDSS J1030+0524 [51], shown in Figure 2. The spectrum exhibits a strong Lyman $\alpha$ Gunn-Peterson (GP) trough, with no detectable flux between wavelengths corresponding to redshifts $5.97 < z < 6.20$, as well as a somewhat narrower Lyman $\beta$ trough between $5.97 < z < 6.18$ [51], as shown in Figure 2. The flux detection threshold in the Lyman $\alpha$ and Lyman $\beta$ regions of this spectrum
correspond to Lyman $\alpha$ optical depths of $\tau_{\text{lim(Ly}\alpha)} \approx 6.3$ and $\tau_{\text{lim(Ly}\beta)} \approx 22.8$ respectively.

To summarize these constraints, we have divided the spectrum into three regions, shown in Figure 1. In Region 1, with $\lambda_{\text{obs}} \geq 8752.5$ Å, the detection of flux corresponds to the upper limit on the optical depth $\tau_{\text{Ly}\alpha} < 6.3$. Region 2, extending from $8725.8$ Å $\leq \lambda_{\text{obs}} < 8752.5$ Å, is inside the Lyman $\alpha$ trough, but outside the Lyman $\beta$ trough. Throughout this region, the data requires $6.3 < \tau_{\text{Ly}\alpha} < 22.8$. Region 3, with $\lambda_{\text{obs}} < 8725.8$ Å has a lower limit $\tau_{\text{Ly}\alpha} \geq 22.8$. As defined, each of these three regions contains approximately eight pixels.

We modeled [37] the absorption spectrum, attempting to match the gross observed features. We utilized a hydrodynamical simulation that describes the density distribution surrounding the source quasar at $z = 6.28$. We extracted density and velocity information from 100 randomly chosen lines of sight (LOSs) through the simulation box. Along each line of sight (LOS), we computed the Lyman $\alpha$ absorption as a function of wavelength. The size of the ionized region ($R_S$) and the fraction of neutral hydrogen outside it ($x_{\text{HI}}$), and the quasar’s ionizing luminosity, $L_{\text{ion}}$, were free parameters. Note that changing $R_S$ moves the dashed ($\tau_D$) curve in Figure 1 left and right, while changing $x_{\text{HI}}$ moves it up and down; changing $L_{\text{ion}}$ moves the solid ($\tau_R$) curve up and down. We evaluated $\tau_R$ and $\tau_D$ for each LOS, and for each point in a three-dimensional parameter space of $R_S$, $x_{\text{HI}}$, and $L_{\text{ion}}$, we computed the fraction of the LOSs that were acceptable descriptions of the spectrum of SDSS J1030+0524, based on the criteria defined above.

The procedure outlined above turns out to provide tight constrains on all three of our free parameters simultaneously. In particular, we find the allowed range for the radius of the Str"omgren sphere to be $42 \text{ Mpc} \leq R_S \leq 47 \text{ Mpc}$, and a $\sim 1 \sigma$ lower limit on the neutral fraction of $x_{\text{HI}} \gtrsim 0.17$. These results can be interpreted as follows. As mentioned previously, the presence of flux in Region 2 ($\tau_{\text{Ly}\alpha} < 22.8$) sets an immediate lower limit on $R_S$. Region 3, however, yields an upper limit on $R_S$, from the requirement that $\tau_{\text{Ly}\alpha} > 22.8$ in that region. This high optical depth cannot be maintained by $\tau_R$ alone, without violating the constraint in Region 1 of $\tau_{\text{Ly}\alpha} < 6.3$. We note that tight constraints on the neutral fraction ($x_{\text{HI}} \gtrsim 0.1$) can be obtained from the size of the Str"omgren sphere together with an assumed lower limit on its lifetime [54]. Our direct determination of the Str"omgren sphere size is only slightly larger than the value assumed in [54], lending further credibility to this conclusion.

Our direct constraint on the neutral hydrogen fraction, $x_{\text{HI}}$, on the other hand, comes from the presence of flux in the Lyman $\beta$ region of the spectrum corresponding to Region 2. Because of fluctuations in the density field (and hence

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1 For our purposes, these optical depths can be taken as rough estimates. Their precise values are difficult to calculate, with $\tau_{\text{lim(Ly}\beta)}$ especially uncertain [45,30,8,11]. However, we have verified that our conclusions below remain unchanged when the threshold opacities are varied well in excess of these uncertainties. In particular, considering ranges as wide as $5.5 < \tau_{\text{lim(Ly}\alpha)} < 7$ and $10 < \tau_{\text{lim(Ly}\beta)} < 30$ would lead to constraints similar to those we derive below.
in $\tau_R$), a strong damping wing is needed to raise $\tau_{\text{Ly}\alpha}$ above 6.3 throughout Region 2, while still preserving $\tau_{\text{Ly}\alpha} < 6.3$ in Region 1. This result is derived from the observed sharpness of the boundary of the HII region alone, and relies only on the gross density fluctuation statistics from the numerical simulation. In particular, it does not rely on any assumption about the mechanism for the growth of the HII region.

Using a large sample of quasars (and/or a sample of gamma-ray burst afterglows with near-IR spectra) at $z > 6$, it will be possible to use the method presented here to locate sharp features in the absorption spectrum from intervening HII regions, not associated with the target source itself. The Universe must have gone through a transition epoch when HII regions, driven into the IGM by quasars and galaxies, partially percolated and filled a significant fraction of the volume. The detection of the associated sharp features in future quasar absorption spectra will provide a direct probe of the the 3D topology of ionized regions during this crucial transition epoch (in particular, it should enhance any constraint available from either the Lyman $\alpha$ or $\beta$ region alone [14]).

3 Did Accreting Black Holes Contribute to Reionization?

The two most natural types of UV sources that could have reionized the IGM are stars or accreting black holes. Deciding which of these two sources dominated the ionization has been studied for over 30 years (e.g. [2]). It has become increasingly clear over the past decade that the ionizing emissivity of the known population of bright quasars diminishes rapidly beyond $z \gtrsim 3$, and they are unlikely to contribute significantly to the ionizing background at $z \gtrsim 5$ [44,18].

This, however, leaves open two possibilities. First, if low-luminosity, yet undetected miniquasars are present in large numbers, they could still dominate the total ionizing background at $z \sim 6$ [21]. Second, the supermassive black holes at $z \sim 6$ must be assembled from lower-mass seeds which accrete and merge during the hierarchical growth of structure. The population of accreting seed BHs can contribute to the ionization of the IGM at $z \sim 20$ [32,41].

The above two possibilities can both involve faint BHs that are not individually detectable. However, a population of accreting BHs at $z \gtrsim 6$ would be accompanied by the presence of an early X-ray background. Since the IGM is optically thick to photons with energies $E$ below $E_{\text{max}} = 1.8[(1 + z)/15]^{0.5}x_{\text{HI}}^{1/3}$ keV, the soft X-rays with $E \lesssim E_{\text{max}}$ would be consumed by neutral hydrogen atoms and contribute to reionization. However, the background of harder X-rays would redshift without absorption and would be observed as a present-day soft X-ray background (SXB). Under the hypothesis that accreting BHs are the main producers of reionizing photons in the high-redshift universe, it is a relatively straightforward exercise to calculate their contribution to the present-day SXB.

We assumed for simplicity [9] that the accreting BHs form in a sudden burst at redshift $z = z_Q$. The total number of BHs was expressed by a normalization constant $\eta$, defined as the ratio of the total number of ionizing photons emitted per unit volume produced by the BH population to the number density of hy-
drogen atoms. Full ionization of the IGM at $z \sim 6$, where recombinations are significant, likely requires $\eta \gtrsim 10^{18}$ [18]. We find that in order to account for the electron scattering optical depth $\tau_e \sim 0.17$ by partially (pre–)ionizing the IGM at $z \sim 15$, a somewhat smaller $\eta$ is sufficient (see below).

The spectrum of the ionizing background is a crucial ingredient of the modeling, and depends on the type of accreting BH that is considered. For luminous quasars powered by supermassive black holes, we adopted a composite spectrum [42], based on the populations of lower redshifts ($0 < z < 5$) QSOs. The spectra of lower–mass mini–quasars, with BHs whose masses are in the range $M_{bh} \approx 10^{2–4} M_\odot$, are likely to be harder. For these sources, we followed [32] and adopted a two–component template that includes a multi–temperature accretion disk, and a simple power-law emission to mimic a combination of Bremsstrahlung, synchrotron, and inverse Compton emission by a non–thermal population of electrons.

Finally, we took the unresolved soft X–ray band in the energy range $0.5 – 2.0$ keV to be in the range $(0.35 – 1.23) \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$. This range was obtained [9] from a census of resolved X–ray sources, which we subtracted from the total SXB. We included the uncertainties in both the measurement of the
total SXB (which was dominant) and in the number of resolved point sources. We examined a range of X–ray energies, and found the strongest constraints in the 0.5 – 2 keV band. We note that a recent study [4] of faint X–ray sources found a significant population of star–forming galaxies among these sources, with a steeply increasing fractional abundance (over AGNs) toward low X–ray luminosities. If this trend continues to a flux limit that is only modestly below the current point–source detection threshold in the deepest Chandra fields, then the SXB would be saturated, strengthening our constraints (leaving less room for any additional, high–z quasars).

We find that models in which $z > 6$ accreting BHs alone fully reionize the universe saturate the unresolved X–ray background at the $\geq 2\sigma$ level. Pre–ionization by miniquasars requires fewer ionizing photons, because only a fraction of the hydrogen atoms need to be ionized, the hard X–rays can produce multiple secondary ionizations, and the clumping factor is expected to be significantly smaller than in the UV–ionization case [18,39]. We find that models in which X–rays are assumed to partially ionize the IGM up to $x_e \sim 0.5$ at $6 \lesssim z \lesssim 20$ are still allowed, but could be constrained by improved future determinations of the unresolved component of the SXB.

As emphasized above, the spectral shape of the putative typical high–z accreting BH is uncertain; the existing templates, motivated by lower–redshift sources, can be considered merely as guides. Figure 3 shows which combinations of $\alpha$ (the logarithmic slope of the ionizing spectrum) and $\eta$ are allowed by the unaccounted flux in the SXB (the solid and dotted curves cover our inferred range of the unresolved SXB). This figure shows that for $\eta = 10$, a power–law shallower than $\alpha \approx 1.2 - 1.4$ will saturate the unaccounted flux. For comparison, $\alpha$ is in the range $-1.5 \lesssim \alpha \lesssim -0.5$ for $z \lesssim 0.3$, and $-1.2 \lesssim \alpha \lesssim -0.6$ for $1 \lesssim z \lesssim 6$ for optically selected radio quiet quasars [49].

Our constraints derive from the total number of ionizing photons that the population as a whole needs to produce to either fully or partially reionize the universe. Therefore, our conclusions depend mostly on the assumed spectral shape and the required number of ionizing photons per hydrogen atom $\eta$. They are independent of the details of the population, such as the luminosity function and its evolution with redshift. Future improvements in resolving the SXB, improving the limits on the unresolved component by a factor of a few, would place stringent constraints on the contribution of $z \sim 15$ accreting BHs to the scattering optical depth measured by WMAP.

4 How Did Black Holes Grow by Accretion and Mergers?

Since the seeds of early BHs may have played a role in reionization, it is all the more interesting to ask how the earliest BH population was formed, and how it evolved. The remnants of metal–free population III stars that form in the first collapsed dark halos can serve as the initial $\sim 100M_\odot$ seeds that later accrete and merge together, to give rise to the supermassive BHs making up the quasar population at $0 < z < 6$, and the remnant BHs found at the centers of local...
galaxies. Several recent studies [29,35,50,28] have addressed various aspects of
the evolution of the BH populations, using the underlying merger trees of dark
matter halos.
Recent work on the generation of gravitational waves during the coalescence
of a binary black hole [13,36] has suggested that the binary experiences a typical
gravitational recoil velocity that may be as large as $\gtrsim 100$ km s$^{-1}$. These
velocities exceed the escape velocity $v_{\text{esc}}$ from typical dark matter halos at high–
redshift ($z \gtrsim 6$), and can therefore disrupt the early stages of growth of BHs by
ejecting the earliest seeds from their host galaxies. BHs can then start growing
effectively only once the typical dark matter potential wells are sufficiently deep
 to retain the recoiling BHs.
Relatively little time is available for the growth of few $\times 10^9$ M$_\odot$ SMBHs prior
to $z \sim 6$, and their seed BHs must be present as early as $z \sim 10$ [24]. A model
in which stellar seed BHs appear in small progenitor DM halos is consistent
with the presence of a $\sim 4 \times 10^9$ M$_\odot$ SMBH at $z \sim 10$, provided that each
seed BH can grow at least at the Eddington–limited exponential rate, and that
the progenitor halos can form seed BHs sufficiently early on [24], in halos with
velocity dispersions of $\sigma \sim 30$ km/s.
We quantified the effect of gravitational recoil on the growth of a few $\times 10^9$ M$_\odot$
black hole [17], by assuming that progenitor holes are ejected from DM halos
with velocity dispersions $\sigma < v_{\text{kick}}/2$, and do not contribute to the final BH mass.
Each halo more massive than this threshold was assumed to host a seed BH that
accretes at the Eddington rate, and the BHs were assumed to coalesce when their
parents halos merged. We took, as an example, the SMBH powering the most
distant SDSS quasar, SDSS 1054+1024 at redshift $z = 6.43$, with an inferred BH
mass of $\sim 4 \times 10^9$ M$_\odot$. We find that recoil velocities with $v_{\text{kick}} \gtrsim 65$ km s$^{-1}$ must
occur infrequently, or else this SMBH must have had a phase during which it
gained mass significantly more rapidly than an Eddington–limited exponential
growth rate (with a radiative efficiency of $\sim 10\%$) would imply. The super–
Eddington growth phase can be avoided [55] if seed BHs can form and grow by
mergers in dark halos with a velocity dispersion as small as $\sigma \approx 5$ km/s, the halos
have steep density profiles (increasing the escape velocity [33] from the central
regions by a factor of $\gtrsim 5$ relative to the naive formula $v_{\text{esc}} = 2\sigma$), and the BHs
that are retained during the mergers of their halos can grow uninterrupted at
the Eddington rate between their birth and $z \approx 6$.

5 Can We Detect Massive $z > 6$ BHs Directly?

A natural question to ask is whether massive BHs at $z > 6$ can be directly
detected. While the SDSS has detected a handful of exceptionally bright, few
$\times 10^9$ M$_\odot$ black holes (the BH mass is inferred assuming these sources shine at
the Eddington luminosity), they are likely a “tip of the iceberg”, corresponding
to the rare massive tail of the BH mass function. In X–rays bands, the deepest
Chandra fields have reached the sensitivity to detect nearly $\sim 100$ times smaller
holes ( [23], provided they radiate the Eddington luminosity, with a few percent
of their emission in the X-ray bands). However, due to the small size of these fields, they have revealed only a handful of plausible candidates [1,3].

Detections however, seem promising in the large radio survey, FIRST. We used a physically motivated semi-analytic model, based on the mass function of dark matter halos, to predict the number of radio-loud quasars as a function of redshift and luminosity [25]. Simple models, in which the central BH mass scales with the velocity dispersion of its host halo as $M_{bh} \propto \sigma_{\text{halo}}^5$ have been previously found to be consistent with a number of observations, including the optical and X-ray quasar luminosity functions [21,53]. We find that similar models, when augmented with an empirical prescription for the radio loudness distribution, overpredict the number of faint ($\sim 10\mu$Jy) radio sources by 1–2 orders of magnitude. This translates into a more stringent constraint on the low-mass end of the quasar black hole mass function than is available from the Hubble and Chandra Deep Fields. We interpret this discrepancy as evidence that black holes with masses $\lesssim 10^7 M_\odot$ are either rare or are not as radio-loud as their more massive counterparts. Models that exclude BHs with masses below $10^7 M_\odot$ are in agreement with the deepest existing radio observations, but still produce a significant tail of high-redshift objects. In the 1-10GHz bands, at the sensitivity of $\sim 10\mu$Jy, we find surface densities of $\sim 100$, $\sim 10$, and $\sim 0.3$ deg$^{-2}$ for sources located at $z > 6$, 10, and 15, respectively. The discovery of these sources with instruments such as the Allen Telescope Array (ATA), Extended Very Large Array (EVLA), and the Square Kilometer Array (SKA) would open a new window for the study of supermassive BHs at high redshift. We also find surface densities of $\sim 0.1$ deg$^{-2}$ at $z > 6$ for mJy sources that can be used to study 21 cm absorption from the epoch of reionization. These models suggest that, although not yet optically identified, the FIRST survey may have already detected several thousand such $> 10^8 M_\odot$ BHs at $z > 6$.

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