A CONSTRAINT ON THE GRAVITATIONAL LENSING MAGNIFICATION AND AGE OF THE REDSHIFT $z = 6.28$ QUasar SDSS 1030+0524

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ABSTRACT

The recent discovery of bright quasars at redshift $z \sim 6$ suggests that black holes (BHs) with masses in excess of $\sim 10^9 M_{\odot}$ have already assembled at a very early stage in the evolution of the universe. An alternative interpretation is that these quasars are powered by less massive BHs, but their fluxes are strongly magnified through gravitational lensing by intervening galaxies. Here we analyze the flux distribution of the Ly$\alpha$ emission of the quasar with the highest known redshift, SDSS 1030+0524, at $z = 6.28$. We show that this object cannot have been magnified by lensing by more than a factor of $\sim 5$. 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. Based on the line/ratio continuum of SDSS 1030+0524, we further argue that this quasar also cannot be beamed by a significant factor. We conclude that the minimum mass for its resident BH is $4 \times 10^9 M_{\odot}$, consistent with a large fraction of the rest-mass energy of the total BH mass in their presumed remnants at redshift $z = 0$ (see, e.g., the recent paper Yu & Tremaine 2002, and references therein). Conversely, this implies that SMBHs have grown most of their mass in a luminous phase, accreting no faster than the Eddington rate, corresponding to exponential growth on the timescale of $t_{\text{edd}} = 4 \times 10^7 (\epsilon/0.1)$ yr. With the recent discovery of four quasars around redshift $z \approx 6$ in the Sloan Digital Sky Survey (SDSS), it appears that bright quasar activity already commenced at this early epoch. Under the assumption that these quasar BHs shine at their Eddington limit and they are not gravitationally lensed or beamed, their masses are $\sim (2-3) \times 10^9 M_{\odot}$. As emphasized by Haiman & Loeb (2001), the time it takes for a SMBH to grow to this size from a stellar seed of $\sim 100 M_{\odot}$ is $4 \times 10^7 \ln(3 \times 10^9/100)$ yr, comparable to the age of the universe at $z = 6$ ($\sim 9 \times 10^8$ yr for a flat $\Lambda$CDM universe with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.3$).

SMBHs at such an early stage in the evolution of the universe can thus only be marginally accommodated into our currently popular cosmological models. Furthermore, their existence implies that the seeds of these SMBHs had to appear at very high redshifts ($z \geq 10$) and also places constraints on the physics of how SMBHs grow. In particular, their growth could not have been much slower than the Eddington rate under a nominal 10% radiative efficiency, and high efficiencies ($\geq 20\%$) can already be ruled out (see, e.g., Haiman & Loeb 2001 for details).

Such conclusions rely on the fact that the SMBHs are indeed very massive. The masses of SMBHs in luminous quasars are uncertain to the extent that the quasars’ emission may be magnified through gravitational lensing by foreground objects (e.g., Turner 1991). Indeed, it is possible to consider the statistics of intervening lenses, together with a luminosity function (LF) of $z \sim 6$ quasars, to estimate the expected probability that the SDSS quasars were significantly magnified. The $z = 6$ quasar LF is very poorly constrained, and even strong magnifications can have large probabilities if the LF is steep (Comerford, Haiman, & Schaye 2002; Wyithe & Loeb 2002a, 2002b). Strong magnification of the SDSS quasars could therefore constitute an alternative explanation to their high BH masses. To a lesser level, the inferred masses of the SMBHs are also subject to variations of parameters in the assumed cosmological model.

A separate question concerns the lifetime of quasars. Unlike the lifetime of stars, which may be computed accurately theoretically, the lifetime of quasars is largely unknown because of large uncertainties in BH accretion.

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physics (i.e., radiation efficiency) and gas supply. As a result, constraints on the lifetime of quasars can be placed only empirically and indirectly. The very convincing evidence for the existence of massive BHs in majority of normal galaxies (Magorrian et al. 1998; Richstone et al. 1998; Genzel & Eckart 1999; Tremaine et al. 2002) implies that a typical lifetime of quasars of \( t_{\text{Hubble}} n_q n_G \sim 10^7 \) yr, where \( t_{\text{Hubble}} \) is the Hubble time and \( n_q \) and \( n_G \) are the observed number density of quasars and normal galaxies, respectively (Blandford 1999). An upper limit on quasar lifetime of \( 10^9 \) yr may be inferred based on the low-redshift (\( z \leq 3 \)) decrease of quasar abundance. The comparison of quasar clustering properties and simulated galaxy halos of comparable clustering properties can also be used to infer a quasar lifetime of \( 10^8 - 10^9 \) yr (Haiman & Hui 2001; Martini & Weinberg 2001). Finally, a quasar lifetime of \( 10^7 \) yr has recently been inferred from the He \( \text{ii} \) proximity region of a quasar embedded in an intergalactic medium (IGM), where helium is mostly in the form of He \( \text{ii} \) (at \( z \geq 3 \), see, e.g., Anderson et al. 1999; this is similar to our own method, but yields an independent constraint).

In this paper, we focus our attention on the bright quasar with the highest known redshift, SDSS 1030+0524 at \( z = 6.28 \). We analyze the spectrum of this source to derive interesting constraints both on the BH mass and on the age of this source. This source is unique among the four \( z \approx 6 \) quasars in that it shows a strong Gunn-Peterson (1965) trough and appears to be embedded in a neutral IGM. The spectrum of a point source of Ly\( \alpha \) radiation would show no flux shortward of the central Ly\( \alpha \) wavelength, because of absorption by the intervening neutral IGM. However, some flux may be transmitted shortward of the Ly\( \alpha \) line, provided that the source is surrounded by a sufficiently large local ionized region (Strömgren sphere). In an earlier paper (Cen & Haiman 2000, hereafter CH00), we showed that the transmission of the blue side of the intrinsic Ly\( \alpha \) emission line depends directly on the total number of ionizing photons emitted over the lifetime of the source: i.e., on the product of its lifetime and its intrinsic luminosity (or BH mass). This situation is unique for quasars embedded in a neutral IGM. For less luminous objects, such as galaxies, the damping wing of the resonance Ly\( \alpha \) absorption of the intervening neutral IGM (Miralda-Escudé 1998) would cast a very high optical depth and render most of the intrinsic Ly\( \alpha \) emission invisible. Likewise, a quasar embedded in a highly ionized IGM at lower redshifts rapidly establishes ionization equilibrium, and the “proximity effect” (Bajtlik, Duncan, & Ostriker 1988) in its spectrum reveals no useful constraint about its age.\(^3\) However, a bright quasar at high redshift, prior to cosmological reionization, such as SDSS 1030+0524, can provide a unique way to tightly constrain both the BH mass and the age of the quasar. In this paper, we analyze the spectrum of SDSS 1030+0524 to provide such a quantitative constraint.

The rest of this paper is organized as follows: In § 2 we describe our model for the spectrum of the Ly\( \alpha \) line of a high-redshift source. In § 3 we apply this model to SDSS 1030+0524 to derive a constraint on its lensing magnification and its lifetime. In § 4 we discuss the implications of our results and their caveats. Finally, in § 5 we offer our conclusions. Throughout this paper, we assume the background cosmology to be flat \( \Lambda \)CDM with \((\Omega_{\Lambda}, \Omega_m, \Omega_b, \text{ and } h) = (0.7, 0.3, 0.04, \text{ and } 0.7)\).

2. TRANSMISSION OF THE Ly\( \alpha \) EMISSION LINE

In this section, we simulate the observed spectrum of a quasar near its Ly\( \alpha \) emission line, for a source embedded in a neutral IGM with a given age and BH mass. Our modeling has two basic steps: (1) we place a quasar in the neutral IGM, and compute the size of its ionized (H \( \text{ii} \)) region, and (2) we simulate the spectrum of the emission line by assuming an intrinsic template line shape and by including the effects of the absorbing gas both inside and outside the H \( \text{ii} \) region. For a detailed description of the method, the reader is referred to CH00. Here, we briefly recapitulate.

Ignoring any recombinations, the radius \( R_S \) of the Strömgren sphere of a quasar of age \( t_Q \) is such that the number of hydrogen atoms in the sphere equals the total number of ionizing photons produced by the source

\[
R_S = \left( \frac{3 N_{\text{ph}} t_Q}{4 \pi \langle n_{\text{HI}} \rangle} \right)^{1/3} = 4.5 \left( \frac{N_{\text{ph}}}{1.3 \times 10^{57} \text{ s}^{-1}} \right)^{1/3} \times \left( \frac{t_Q}{2 \times 10^7 \text{ yr}} \right)^{1/3} \left( \frac{1 + z_Q}{7.28} \right)^{-1} \text{ Mpc}
\]

(1)

\[
= 4.5 \left( \frac{M_{\text{bh}}}{2 \times 10^9 \text{ M}_\odot} \right)^{1/3} \times \left( \frac{t_Q}{2 \times 10^7 \text{ yr}} \right)^{1/3} \left( \frac{1 + z_Q}{7.28} \right)^{-1} \text{ Mpc}
\]

(2)

(CH00), where \( R_S \) is in proper (not comoving) units, \( \langle n_{\text{HI}} \rangle \) is the mean hydrogen density within \( R_S \), and \( N_{\text{ph}} \) is emission rate of ionizing photons from the quasar. For \( \langle n_{\text{HI}} \rangle \), we have adopted the mean IGM density at \( z = 6.28 \) with \( \Omega_b = 0.04 \), and \( N_{\text{ph}} = 1.3 \times 10^{57} \text{ s}^{-1} \) is calibrated from the observed flux of SDSS 1030+0524, extrapolating its continuum to energies above 13.6 eV using a standard quasar template spectrum (Elvis et al. 1994, which agrees well with the more recent SDSS template in Vanden Berk et al. 2001, hereafter VdB01). Adopting the same template spectrum, and assuming further that the BH powering this quasar is shining at its Eddington luminosity, the mass of the BH is found to be \( M_{\text{bh}} = 2 \times 10^9 \text{ M}_\odot \). We have used this mass to convert equation (1) into equation (2). The normalization of these equations through the choice of the age \( t_Q \) ensures a match to the observed size of the H \( \text{ii} \) region in the spectrum of SDSS 1030+0524 (see below).

In an evolving and clumpy cosmological density field around a quasar, ionizing photons are lost to recombinations, and the size of the H \( \text{ii} \) region can be reduced relative to the prediction of equation (2). We need to then solve the equation for the radius of the ionization front, \( R_S \), taking into account all relevant effects including recombination, density evolution, and cosmological effects as follows:

\[
\frac{d R_S^3}{dt} = 3H(z) R_S^2 + \frac{3 N_{\text{ph}}}{4 \pi \langle n_{\text{HI}} \rangle} C \langle n_{\text{HI}} \rangle \alpha_B R_S^2,
\]

(3)
where $H(z)$ is the Hubble constant at $z$, $C \equiv \langle n_{\text{H}}^2 \rangle / \langle n_{\text{H}} \rangle^2$ is the mean clumping factor of ionized gas within $R$, and $\alpha_B$ is the hydrogen recombination coefficient. The three terms on the right side of equation (3) account for the Hubble expansion, the ionizations by newly produced photons, and recombinations, respectively (Shapiro & Giroux 1987; Hai-
man & Loeb 1997). Although equation (2) is accurate for low clumping factors and quasar ages ($C < 10$, $t_q < 10^6$ yr), the results presented here are based on a numerical solution of equation (3).

In general, a quasar has an intrinsic Ly$\alpha$ emission line, which is reprocessed along the line of sight to the observer by the opacity of the intervening neutral IGM as well as of the residual neutral hydrogen within the Strömgren sphere. We model the absorption in the two regions separately. The IGM outside the H II region is assumed to be neutral (see discussion below). Inside the H II region, we model the density distribution using the hydrodynamical simulation described in Cen & Loeb (1997). For illustrative purposes, we have chosen here to focus on a single line of sight through this simulation box, which has a mean gas clumping factor of $C = 10$, and an approximate log-normal density distribution. The simulation has a resolution of $\sim 10$ (proper) kpc, about a factor of $\sim 10$ below the Jeans length; the clumping therefore represents a physical smoothing on a $\sim 100$ kpc scale, corresponding to an observed wavelength range of $\Delta \lambda = 0.1$ Å. A full statistical description of the expected flux distribution within the H II region, based on a large sample of lines of sights, is not crucial for our present purposes but will be considered in a future paper (Z. Hai-
man & R. Cen, in preparation).

Finally, in order to model the intrinsic profile of the emission line, we utilize the median Ly$\alpha$ emission line shape as determined observationally by VdB01. We first obtain the line profile from the VdB01 spectrum by subtracting a constant $6.3 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$, which is approximately the median observed continuum level. To fit the red (unabsorbed) side of the Ly$\alpha$ line of SDSS 1030+0524, we find we have to divide the VdB01 profile by a factor of $\approx 3$. To approximate the observed continuum of SDSS 1030+0524, we add back a constant of $1.1 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. In other words, the observed continuum flux of SDSS 1030+0524 is about 6 times fainter than that of the median $z > 2.25$ quasar, while the emission line is only about 3 times fainter. This deviation from the typical line/continuum ratio is significant; the 68% uncertainty in the flux ratio is less than 10%. The VdB01 spectrum is the median spectrum of about $\sim 150$ quasars at $z > 2.25$, with a mean redshift of $z \approx 3$. The IGM has an average opacity of $\tau_{\text{IGM}} \sim 0.4$ at the blue side of the Ly$\alpha$ line at this redshift (e.g., Madau 1995). To create our intrinsic template line shape between 1200 and 1215 Å (8750 and 8850 Å, observed), we divide the VdB01 profile by a correction factor that varies linearly from unity at 1215 Å to $\exp(-\tau_{\text{IGM}})$ at 1200 Å. This is intended to take into account the fact that each quasar in the VdB01 sample suffers from both IGM opacity and from its own proximity effect (so that there is no correction at the line center).

Figure 1 shows the resulting intrinsic Ly$\alpha$ emission line (top solid curve), as well as an illustrative example of the processed profile (bottom solid curve). In this example, we assume a quasar age of $t_q = 2 \times 10^5$ yr, and we adopt the ionizing photon production rate of $N_{\text{ph}} = 1.3 \times 10^{57}$ s$^{-1}$, corresponding to the observed flux of SDSS 1030+0524 with no lensing corrections. This results in a proper H II radius of 4.5 Mpc. The bottom solid curve in Figure 1 shows the resulting reprocessed Ly$\alpha$ emission line, including the H II opacities from both inside and outside the H II region. Also shown in this figure as the dashed curve is the observed flux distribution (Becker et al. 2001).

Our final processed spectrum is in reasonable agreement with the data. There is a discrepancy at the Ly$\alpha$ line center; our model does not account for the large apparent additional opacity centered at the quasar redshift. However, this does not affect our conclusions drawn from the blue tail of the Ly$\alpha$ line. The crucial feature of the observed spectrum of SDSS 1030+0524 is the presence of significant flux down to 8750 Å. Any model that allows for the presence of this flux must have a H II region whose size is at least less than 4.5 Mpc, as is the case in the example shown in Figure 1. If the H II region was smaller, the flux at wavelengths above 8750 Å would be suppressed by an enormous factor [~$\exp(10^6)$] from the Gunn-Peterson (1965) opacity of the neutral IGM.

3. CONSTRAINTS ON LENSING MAGNIFICATION AND THE AGE OF SDSS 1030+0524

As we have seen above, the presence of flux in the spectrum of SDSS 1030+0524 down to 8750 Å implies that this quasar is surrounded by a large (4.5 proper Mpc) Strömgren sphere. Assuming that its apparent flux reflects its true luminosity, this source is powered by a BH whose mass is
$M_{\text{bh}} = 2 \times 10^9 M_\odot$ and, from equation (1), whose age has to be at least $2 \times 10^7$ yr.\footnote{The age could be shorter (longer) if the source was brighter (fainter) in the past. However, SDSS 1030+0524 is already unusually bright; being even brighter would make the BH even more puzzlingly massive.}

However, the flux of SDSS 1030+0524 may be magnified through gravitational lensing by foreground galaxies (or stars). As mentioned in § 1, the probability for significant magnification can be appreciable, depending on the shape of the unknown quasar luminosity function (Comerford et al. 2002; Wyithe & Loeb 2002a, 2002b). Obviously, for a given observed flux from the quasar, a larger gravitational lensing magnification would imply an intrinsically fainter quasar. A fainter quasar would, in turn, require a longer age to produce a Strömgren sphere with the required size of at least 4.5 Mpc. Thus, the minimum quasar age is an increasing function of gravitational lensing magnification. Indeed, a constraint on $t_{\text{min}}$ may be most informatively placed in the $t_{\text{min}}$ versus magnification plane.

Figure 2 shows the constraints on the minimum age of SDSS 1030+0524 as a function of its gravitational lensing magnification. The constraint is based on the requirement that the radius of the Strömgren sphere, computed from equation (3), should be $R_{\text{S}} = 4.5$ Mpc. The case presented here assumes that the IGM is still largely neutral at $z = 6.28$. The four curves show four cases with $\alpha = 0$ (ignoring recombinations, in this case, $t_{\text{min}}$ scales linearly with the magnification) and with three different gas clumping factors, $C = 1$, $C = 10$, and $C = 20$. The upper shaded region is excluded because it exceeds the age of the universe at $z = 6.28$.

Several important points may be learned from Figure 2. First, $t_{\text{min}} < 2 \times 10^7$ yr is not allowed for any value of magnification; $t_{\text{min}} = 2 \times 10^7$ yr is an absolute lower limit. Percerici et al. (2002) derive the age of SDSS 1030+0524 to be $1.33 \times 10^7$ yr by simply counting ionizing photons at $z = 6.28$. They do not take into account the evolution of the density field and hydrogen recombination. While we have performed more detailed calculations, we stress that in either case the derived age of the quasar can only be a lower bound, since locally (e.g., at $\lambda \geq 8750$ Å) the transmission of rest-frame Ly\,$\alpha$ photons is determined by the balance between quasar ionizing flux and hydrogen recombination, once the required age is reached.

Second, the maximum allowed gravitational lensing magnification is a strong function of the assumed clumping factor. For large clumping factors, the size of the H\,$\Pi$ region lags increasingly behind its value in the no-recombination case, and increasingly longer ages are required. Note that for $C > 10$, the H\,$\Pi$ sphere reaches its (steady state) equilibrium value in a few times $10^6$ yr, after which it ceases to grow. Figure 2 also reveals that for realistic clumping factors ($C > 20$, see discussion below), the magnification cannot exceed a factor of 5. Even for a clumping factor as low as $C = 10$, the magnification must be less than a factor of 10. Note that for $C = 10$, if the quasar was magnified by the maximum possible factor of 9, $R_{\text{S}} = 4.5$ (proper) Mpc corresponds to the equilibrium sphere radius, which is reached in $10^{8.5}$ yr. In this case, the size of the Strömgren sphere ceases to increase once its age reaches $10^{8.5}$ yr, regardless of when it was turned on. In other words, if the gravitational lensing magnification is 9, the quasar had to be turned on at some redshift prior to $z \sim 10$. In the more likely case of $C = 20$, by the same argument, the quasar could only have been magnified by a factor of 5 if it turned on at $z \gtrsim 9$. To summarize: each SDSS quasar at $z \sim 6$ could have a significant probability of having being magnified through gravitational lensing by a factor of $\gtrsim 10$ (Comerford et al. 2002; Wyithe & Loeb 2002a, 2002b), potentially casting doubt on the validity of the derived large BH masses. However, here we find that SDSS 1030+0524 cannot be gravitationally magnified by more than a factor of $\sim 5$.

4. DISCUSSION

Our conclusions above, most importantly that SDSS 1030+0524 cannot be an intrinsically faint and strongly lensed source, relies only on the need for this source to create a Strömgren sphere with a radius at least 4.5 Mpc. In particular, the conclusions are insensitive to the detailed modeling of the density distribution near the quasar. Our most important assumption is that the IGM is largely neutral at $z = 6.28$, a statement supported by the detection of the Gunn-Peterson (1965) trough in the spectrum of this source. Although it would be possible to block out the flux of SDSS 1030+0524 at wavelengths shorter than 8750 Å even if the neutral fraction was $x_{\text{HI}} \sim 10^{-2}$ (Becker et al. 2001; Barkana 2001; Fan et al. 2002), the inferred rapid rise of the metagalactic radiation field from $z \sim 5.5$ to $z \sim 6.3$ suggests that the universe is indeed neutral at the redshift of this source (Cen & McDonald 2002; Gnedin 2001). A comparison between the observed ionizing background flux evolution and numerical simulations indeed shows a strong case. Simulations have shown that the reionization phase begins with a relatively slow process on a timescale of about...
a Hubble time, during which the mean radiation field builds up to a value of approximately $10^{-24}$ ergs cm$^{-2}$ Hz$^{-1}$ s$^{-1}$ sr$^{-1}$ at the Lyman limit. This is followed by a brief “overlap” phase, when the majority of the baryons are ionized, accompanied by a sudden jump in the amplitude of the mean radiation field intensity at the Lyman limit to $10^{-22}$ to $10^{-21}$ ergs cm$^{-2}$ Hz$^{-1}$ s$^{-1}$ sr$^{-1}$, which occurs within a redshift interval of a fraction of unity (Miralda-Escudé, Haehnelt, & Rees 2000). If we identify the observed sudden rise of the ionizing background at $z \sim 6.1$ with the epoch of rapid increase in the ionizing radiation background seen in simulations, the baryons must largely be neutral at $z \sim 6.28$.

An important input to our model is the mean clumping of the gas in the IGM. Cosmological simulations of the canonical ΛCDM model yield $C_{H_{II}} \sim 40$ (Fig. 2 in Gnedin & Ostriker 1997) at $z \sim 6$. Note that the model adopted in Gnedin & Ostriker (1997) has $\sigma_8 = 0.67$, which is perhaps rather conservative and consistent with the newer, lower normalization based on X-ray clusters (Seljak 2001). A somewhat different clumping factor may be predicted in a model that self-consistently reionizes the universe at $z \sim 6$ instead of $z \sim 7$ in the simulation. However, it seems unlikely that $C$ can be as low as 10 for a sensible model.

It is also worth pointing out that although the apparent H II region around SDSS 1030+0524 is large, it is $\sim 200$ times smaller than the separation of the bright SDSS quasars implied by their space density (Fan 2001). If faint quasars exist that are $\gtrsim 10^6$ times more abundant, then there could be more than one such source within the inferred H II region around SDSS 1030+0524. However, it is unlikely that such faint sources can significantly contribute to the ionization of the H II region without overproducing the observed ionizing background at $z \sim 6$ (see further discussion in Comerford et al. 2002).

An alternative way to avoid a large BH mass in SDSS 1030+0524 would be if this source has a low total luminosity but is strongly beamed toward us. A test of this hypothesis is the line/continuum ratio. The Einstein radius of a cosmological galaxy-sized lens is around $\sim 1$ kpc, likely larger than the line-emitting region, so that gravitational lensing likely magnifies the line and continuum emission by the same amount (if the line was less magnified, this would strengthen our conclusion below, since the intrinsic (unlensed) line/continuum ratio would then be higher than observed). For a given observed continuum ionizing flux, a presence of beaming into a solid angle $\Omega$ would reduce the strength of any isotropic emission line by a factor of $\Omega/4\pi$, since the lines would only be produced only within the cone into which the ionizing radiation is beamed. As we have seen above, the line/continuum ratio of SDSS 1030+0524 is about twice that of the median $z > 2.25$ quasar. This indicates that SDSS 1030+0524 is less likely to be significantly beamed than a typical high-redshift optical quasar. On the other hand, a typical quasar is indeed unlikely to be significantly beamed: (1) typical optical quasars do not show relativistic spectral features similar to those found in BL Lac objects, which are known to be beamed; (2) there is no indication as to why a typical quasar is different from lower luminosity AGNs and Seyfert galaxies that are known not to be beamed; (3) there is no natural mechanism to produce a strongly beamed radiation whose spectrum remains close to a blackbody, as is seen in the “blue bump” component in the spectra of many quasars; and (4) assuming no beaming, the characteristic luminosities and abundances of bright quasars near $z \sim 2.5$ are consistent with the characteristic masses and abundances of their remnant BHs at $z = 0$ (see, e.g., Yu & Tremaine 2002); strong beaming would likely invalidate this successful agreement.

Combining this with the finding above that the quasar is not magnified through gravitational lensing by a significant factor implies that SDSS 1030+0524 indeed needs to contain a very massive BH. Assuming the quasar radiates at the Eddington luminosity and magnified through gravitational lensing by a factor of 5, the minimum mass for its resident BH is $4 \times 10^9 M_\odot$, and it then has to have formed at redshift $z > 9$.

5. CONCLUSIONS

We have analyzed the flux distribution of the Ly$\alpha$ emission of the quasar with the highest known redshift, SDSS 1030+0524 at $z = 6.28$, discovered by the Sloan Digital Sky Survey. From its spectrum, we infer the presence of a large ($\sim 4.5$ Mpc) ionized region around this quasi-stellar object. The large size of this ionized region makes it impossible for this source to be intrinsically faint, or to be very young. We find that SDSS 1030+0524 could not have been magnified through gravitational lensing by more than a factor of $\sim 5$. The line/continuum ratio of SDSS 1030+0524 is observed to be twice that of the median $z > 2.25$ quasar, indicating that this quasar is also unlikely to be significantly beamed. Combining these two facts requires that the minimum mass for its resident BH is indeed $\sim 10^9 M_\odot$. If the quasar is not lensed and is shining at (or below) the Eddington luminosity of its resident SMBH, then the inferred mass is at least $M_{\text{bh}} = 2 \times 10^9 M_\odot$, and its minimum age is $2 \times 10^7$ yr. These numbers can only be modified by gravitational lensing by relatively small factors: if the source is magnified by the maximum allowed factor of 5, the BH mass is $\sim 4 \times 10^8 M_\odot$, and, in this case, its age has to be longer than $10^8$ yr, placing its formation redshift at $z_f > 9$.

As the formation of such massive BHs in the universe at such high redshifts is already presenting a theoretical challenge, it is important to have limits on the magnification of their fluxes by gravitational lensing. Although SDSS 1030+0524 is currently the only high-redshift quasar to which our method is applicable, the constraints we have derived for this source can be repeated and applied to future quasars that will be discovered at $z \gtrsim 6.3$, prior to the reionization epoch.

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