Spectral signature of cosmological infall of gas around the first quasars

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Recent observations have shown that, only a billion years after the Big Bang, the Universe was already lit up by bright quasars\(^1\) fuelled by the infall of gas onto supermassive black holes. The masses of these early black holes are inferred from their luminosities to be \(>10^9\) solar masses \((M_\odot)\), which is a difficult theoretical challenge to explain. Like nearby quasars, the early objects could have formed in the central cores of massive host galaxies. The formation of these hosts could be explained if, like local large galaxies, they were assembled gravitationally inside massive \((>10^{12}M_\odot)\) halos of dark matter\(^2\). There has hitherto been no observational evidence for the presence of these massive hosts or their surrounding halos. Here we show that the cosmic gas surrounding each halo must respond to its strong gravitational pull, where absorption by the infalling hydrogen produces a distinct spectral signature. That signature can be seen in recent data\(^3,4\).

We model the effect of resonant Ly\(\alpha\) absorption by infalling gas on the quasar light (Figure 1). For each quasar we consider the history of the formation of its host halo from an initial positive overdensity of dark matter. For the initial surrounding density profile at high redshift we adopt the typical profile expected around the dense region that collapses to form
the halo\textsuperscript{5}. This profile as well as the approximation of a spherical geometry are particularly satisfactory for the very rare and massive halos under consideration. We calculate gas infall down to the radius of the accretion shock, and neglect any Ly\alpha absorption due to the post-shock gas. The hot ($\gtrsim 10^7$K) post-shock gas should be fully-ionized by collisions. Part of it is expected to subsequently cool and collapse onto the galactic disk, but Compton heating by the quasar should keep the virialized gas hotter than $\sim 10^6$K. Even if a thin cold shell of shocked gas remains, it will not change the basic pattern produced by infalling gas since the post-shock gas no longer has a high infall velocity.

In order to predict the Ly\alpha absorption around a quasar we must estimate the mass of its host halo. A tight correlation has been measured in local galaxies between the mass of the central black hole and the bulge velocity dispersion\textsuperscript{6,7}. This relation also fits all existing data on the luminosity function of high-redshift quasars within a simple model\textsuperscript{8} in which quasar emission is assumed to be triggered by mergers during hierarchical galaxy formation. We use the best-fit\textsuperscript{6,7,8} relation, in which the black hole mass in units of $10^8 M_\odot (M_8)$ is related to the circular velocity at the halo boundary in units of 300 km s$^{-1}$ ($V_{300}$) by $M_8 = 1.5(V_{300})^5$. For the typical quasar continuum spectrum, we adopt a power-law shape of $F_\nu \propto \nu^{-0.44}$ in the rest-frame range 1190–5000 Å based on the Sloan Digital Sky Survey (SDSS) composite spectrum\textsuperscript{9}, and $F_\nu \propto \nu^{-1.57}$ at 500–1190 Å using the composite quasar spectrum from the Hubble Space Telescope\textsuperscript{10}. Based on observations in soft X-rays\textsuperscript{11}, we extend this power-law towards short wavelengths.

We assume that the brightest quasars shine at their Eddington luminosity, and we note that for the SDSS composite spectrum\textsuperscript{9}, the total luminosity above 1190 Å equals 1.6 times the total continuum luminosity at 1190–5000 Å. Thus, ionizing photons stream out of the quasar’s galactic host at the rate $\dot{N} = 1.04 \times 10^{56} M_8$ s$^{-1}$. We infer the black hole mass using the observed continuum at 1350 Å, with the conversion $F_\nu = 1.74 \times 10^{30} M_8$ erg s$^{-1}$ Hz$^{-1}$. 

Given that helium is doubly-ionized by the quasar, the frequency-averaged photoionization cross-section of hydrogen is for our template spectrum $\bar{\sigma}_H = 2.3 \times 10^{-18} \text{ cm}^2$. The double ionization of helium increases the recombination rate due to the extra electrons, and also produces a characteristic gas temperature of $\sim 1.5 \times 10^4$ K in regions that had already been reionized by a softer ionizing background\textsuperscript{12}.

Only a limited number of published spectra are currently available for a clear test of our predictions. First, only the brightest quasars, which reside in the most massive halos, produce strong infall over a large surrounding region. The infalling gas density scales as $(1 + z)^3$ and the shock radius scales as $(1 + z)^{-1}$, so that the absorption optical depth (see below) scales roughly as $(1 + z)^4$ and the absorption feature is much weaker at low redshift. Even at high redshifts, measuring the detailed Ly$\alpha$ line profile is possible only in a high resolution spectrum with an extremely high signal-to-noise ratio.

Figure 2 shows two particularly high-quality spectra and compares them with our model predictions. Both spectra show our predicted double-peak pattern and disagree with the single-peaked profile predicted by previous models that ignored infall. In particular, models that assume a pure Hubble flow firmly predict no absorption at all at positive velocities and only a gradual decline in the transmitted flux toward negative velocities. This slow decline is due to the fact that in these models the gas closest to the quasar produces no absorption since it is fully ionized by the strong ionizing intensity of the quasar. More distant gas recedes along with the universal expansion and absorbs only at negative velocities. Our model, in contrast, firmly predicts a sharp flux cutoff located at a positive velocity. This flux drop corresponds to absorption by gas just outside the accretion shock, and the positive velocity of the cutoff corresponds to the infall velocity. The strong absorption caused by this gas despite exposure to the ionizing flux from the quasar is due to the high density of the infalling gas. This gas is expected to be $\sim 10$–30 times denser than the cosmic mean after
having fallen toward the quasar host halo over the history of its formation.

The infall velocity is proportional to the halo circular velocity and thus
2 to \(M^{1/3}(1 + z)^{3/2}\), in terms of the halo mass \(M\) and the redshift \(z\). The actual physical distance of the accretion shock in the model is 86 kpc and 80 kpc for the quasars at \(z = 4.795\) and \(z = 6.28\), respectively. Our model with infall also fits approximately the secondary peak that is observed on the blue side of the main peak (i.e., at lower velocity). This blue peak corresponds closely to the point of weakest absorption by the infalling gas, although the profile of the intrinsic quasar emission also affects somewhat the precise location of this peak. In this region we do not expect to fit the flux profile in full detail; our model averages over all lines of sight and possible quasar positions, but observable random fluctuations around our predicted mean are expected in each specific spectrum.

However, once we average over the density fluctuations, the prediction of a second peak rather than a smooth fall-off is generic and insensitive to the detailed model assumptions. At a distance \(R\) from the quasar the resonant optical depth depends on \(\rho^2 R^2\), where \(\rho\) is the density including infall; one factor of \(\rho\) comes from the total gas density, the second comes from the H I fraction which increases with \(\rho\) due to recombinations, and the \(R\)-dependence results from the \(R^{-2}\) decline of the ionizing intensity of the quasar. Thus, a second peak should appear as long as infall produces a density profile falling off faster than \(1/R\) (our model predicts \(R^{-3/2}\)) before asymptoting to the cosmic mean value of unity. We note that in our model the position of the blue peak corresponds to absorption by gas at \(R = 0.45\) Mpc \((z = 4.795)\) or 0.41 Mpc \((z = 6.28)\).

Even in each particular spectrum, the more distant region where the flux drops toward zero can be modelled much more robustly. In particular, significant flux is observed at \(\Delta V = -2000 \text{ km s}^{-1}\) \((z = 4.795)\) and \(\Delta V = -3000 \text{ km s}^{-1}\) \((z = 6.28)\), respectively. These relatively distant regions are only weakly affected by infall and the observed positions
translate to a distance from the quasar of 3.8 Mpc \((z = 4.795)\) or 4.2 Mpc \((z = 6.28)\). In models that do not include a clump distribution, the optical depth at these positions is \(\gtrsim 3\), which means that the observed flux requires an intrinsic unabsorbed flux that is 20 times greater. This is clearly impossible regardless of any uncertainties about the intrinsic line shape and the quasar continuum level. To explain the observed flux, the ionizing intensity of the quasar as determined by our template spectrum from the observed continuum would have to be too low by a factor \(> 2\). However, our full model accounts for the fact that part of the cosmic gas falls into dense sheets and filaments and leaves the rest with a density below the cosmic mean. The resonant Ly\(\alpha\) absorption is made up of the separate contributions of gas elements at a variety of overdensities, and since gas in low-density regions absorbs very weakly, clumping actually increases the mean transmission. Thus, our model naturally accounts for the flux observed far from the quasar, with no change required in the quasar spectrum.

Our conclusions are insensitive to the question of whether the H\(\text{II}\) region of the highest redshift quasar is surrounded by a region of neutral hydrogen (due to the fact that the universe had not been fully reionized by \(z = 6.28^{13}\)) or not\(^{14}\); a distant neutral region would only add on the IGM damping wing\(^{15}\) which produces a smooth, gradual suppression that should not alter the basic double-peak pattern. We note that the quasar may possess a velocity offset relative to Hubble flow due, for example, to a violent galactic merger that had originally activated the quasar. However, the close fit that we find between the predicted accretion shock position and the observed flux drop is evidence against the presence of a large velocity offset in the two quasars we have considered. We note as well that if the observed absorption pattern were due to dense gas clouds within the galaxy (for example, in the region feeding the central black hole), then the absorbing gas would be expected to contain heavy elements such as carbon, oxygen, and nitrogen. This gas would then be expected to absorb other emission lines of the quasar in addition to Ly\(\alpha\). Such associated
absorption is absent in the $z = 4.795$ quasar which has several emission lines with well measured profiles\(^3\), suggesting that the absorbing gas has a near-primordial composition as expected for intergalactic gas.

Our models provide the first direct evidence that two characteristic properties of quasars at low redshift are also applicable to bright quasars in the early universe. These properties include the quasar spectral template, which determines the ionizing intensity of the quasar, and the relation between black hole mass and halo velocity dispersion, which we have used to determine the host halo mass. Both observed spectra show a blue peak of about 75\% of the height of the red (positive velocity) peak, and this is roughly matched by the models. However, if we were to increase the ionizing intensity by an order of magnitude then we would predict a blue peak at least of equal height to the other peak. If, instead, we decreased the ionizing intensity by an order of magnitude then the resulting blue peak would be under 50\% of the height of the red peak and the transmitted flux would decrease to zero toward negative velocities much faster than is observed. Similarly, if we varied the assumed halo mass by more than an order of magnitude then the resulting absorption profile in each quasar would disagree with the data. High-redshift quasars could in principle be much fainter intrinsically than they appear, if they are magnified by gravitational lensing\(^16\); our limits on the ionizing intensity, however, suggest that the two quasars we have modelled cannot be magnified by a factor $\gtrsim 10$.

We can also estimate from the data the total gas infall rates into these massive galaxies. The positions of the accretion shocks imply in our models infall velocities of 400–550 km s\(^{-1}\) and shock radii of 80–90 kpc. Since gas at this radius is expected to have a density of $\sim 20$ times the cosmic mean density\(^5\), we obtain accretion rates of $1300 M_\odot$ yr\(^{-1}\) ($z = 4.795$) and $2900 M_\odot$ yr\(^{-1}\) ($z = 6.28$), respectively. At these rates, the host galaxies of these two quasars could have been assembled in $2\sim 3 \times 10^8$ yr, consistent with the $9 \times 10^8$ yr age of the
universe at $z = 6.28$. Future comparison of our model to the *average* Ly\textsc{\lowercase{a}} absorption profile of a statistical sample of bright, early quasars with similar luminosities and redshifts should allow us to fit the details of the absorption spectrum and refine our quantitative conclusions.
REFERENCES

1. Fan, X., et al., Survey of \( z > 5.8 \) quasars in the Sloan digital sky survey. I. Discovery of three new quasars and the spatial density of luminous quasars at \( z \sim 6 \), \textit{Astron. J.} \textbf{122}, 2833-2849 (2001)

2. Barkana, R., & Loeb, A., In the beginning: the first sources of light and the reionization of the universe, \textit{Phys. Rep.}, \textbf{349}, 125-238 (2001)

3. Zheng, W., et al., Five High-Redshift Quasars Discovered in Commissioning Imaging Data of the Sloan Digital Sky Survey, \textit{Astron. J.} \textbf{120}, 1607-1611 (2000)

4. Becker, R.H., et al., Evidence for reionization at \( z \sim 6 \): Detection of a Gunn-Peterson trough in a \( z = 6.28 \) quasar, \textit{Astron. J.} \textbf{122}, 2850-2857 (2001)

5. Loeb, A., & Eisenstein, D. J., Probing Early Clustering with Lyα Absorption Lines beyond the Quasar Redshift, \textit{Astrophys. J.} \textbf{448}, 17-26 (1995)

6. Ferrarese, L., & Merritt, D., A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies, \textit{Astrophys. J.} \textbf{539}, L9-12 (2000)

7. Tremaine, S., et al., The Slope of the Black Hole Mass versus Velocity Dispersion Correlation, \textit{Astrophys. J.} \textbf{574}, 740-753 (2002)

8. Wyithe, J. S. B., & Loeb, A., A Physical Model for the Luminosity Function of High-Redshift Quasars, preprint astro-ph/0206154 (2002)

9. Vanden Berk, D. E., et al., Composite Quasar Spectra from the Sloan Digital Sky Survey, \textit{Astron. J.} \textbf{122}, 549-564 (2001)

10. Telfer, R. C., Zheng, W., Kriss, G. A., & Davidsen, A. F., The Rest-Frame Extreme-Ultraviolet Spectral Properties of Quasi-stellar Objects, \textit{Astrophys. J.} \textbf{565}, 773-785 (2002)

11. Yuan, W., Brinkmann, W., Siebert, J., & Voges, W., Broad band energy distribution of ROSAT detected quasars. II. Radio-quiet objects, \textit{Astron. Astrophys.} \textbf{330}, 108-122 (1998)

12. Abel, T., & Haehnelt, M. G., Radiative Transfer Effects during Photoheating of the Intergalactic Medium, \textit{Astrophys. J.} \textbf{520}, L13-L16 (1999)
13 Fan, X., et al., Evolution of the Ionizing Background and the Epoch of Reionization from the Spectra of z ~ 6 Quasars, *Astron. J.* **123**, 1247-1257 (2002)

14 Barkana, R., Did the universe reionize at redshift six?, *New Astron.* **7**, 85-100 (2002)

15 Miralda-Escudé, J., Reionization of the Intergalactic Medium and the Damping Wing of the Gunn-Peterson Trough, *Astrophys. J.* **501**, 15-22 (1998)

16 Wyithe, J. S. B., & Loeb, A., Magnification of light from many distant quasars by gravitational lenses, *Nature* **417**, 923-925 (2002)

17 Gunn, J. E., & Gott, J. R., On the Infall of Matter Into Clusters of Galaxies and Some Effects on Their Evolution, *Astrophys. J.* **176**, 1-19 (1972)

18 Bertschinger, E., Self-similar secondary infall and accretion in an Einstein-de Sitter universe, *Astrophys. J. Supp.* **58**, 39-65 (1985)

19 Keshet, U., Waxman, E., Loeb, A., Springel, V., & Hernquist, L., Gamma-Rays from Intergalactic Shocks, preprint astro-ph/0202318 (2002)

20 Abel, T., Bryan, G. L., & Norman, M. L., The formation of the first star in the universe, *Science* **295**, 93-98 (2002)

21 Scharf, C. A., & Mukherjee, R., A statistical detection of gamma-ray emission from galaxy clusters: implications for the gamma-ray background and structure formation, *Astrophys. J.* **580**, 154-163 (2002)

22 Loeb, A., & Waxman, E., Cosmic γ-ray background from structure formation in the intergalactic medium, *Nature* **405**, 156-158 (2000)

23 Gunn, J. E., Peterson, B. A., On the density of neutral hydrogen in intergalactic space, *Astrophys. J.* **142**, 1633-1641 (1965)

24 Bajtlik, S., Duncan, R. C., & Ostriker, J. P., Quasar ionization of Lyα clouds - The proximity effect, a probe of the ultraviolet background at high redshift, *Astrophys. J.* **327**, 570-583 (1988)

25 Haiman, Z., The Detectability of High-Redshift Lyα Emission Lines prior to the Reionization of the Universe, *Astrophys. J.* **576**, L1-L4 (2002)
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Fig. 1.— Schematic illustration of how infall produces a unique spectral signature. A quasar forms inside a galaxy that lies at the center of a massive dark matter halo. A large volume of gas responds to the strong gravitational pull and falls toward the massive halo. As infalling gas impacts on the galactic gas, a strong accretion shock forms. The intrinsic quasar Lyα emission is partially absorbed by the infalling pre-shock gas. In particular, a sharp flux drop is caused by gas (marked with an ×) that is about to hit the accretion shock. This gas is falling toward the quasar at 500 km s^{-1} in this sketch. We calculate spherically-symmetric infall\(^{17}\) and set the accretion shock radius to 1.15 times the halo boundary\(^{18}\), although our results are not altered substantially as long as the shock radius is close to the halo virial radius. Three-dimensional hydrodynamic simulations show that the most massive halos at any time in the universe are indeed surrounded by strong, quasi-spherical accretion shocks\(^{19,20}\). Preliminary evidence has been found for such shocks around nearby galaxy clusters\(^{21,22}\). We model resonant Lyα absorption by intergalactic hydrogen\(^{23}\) that is partially ionized by the radiation produced by the quasar\(^{24}\). In addition to the overall infall pattern\(^{5}\) we include a realistic distribution of gas density fluctuations\(^{25}\). For the distribution of gas clumps we adopt an analytical fit to numerical simulations\(^{26}\). We assume that the clumps are optically thin, and find the neutral fraction separately for each clumping density based on ionization equilibrium with the quasar ionizing flux. We then calculate the mean Lyα transmission averaged over the clump distribution. Note that the absorbed Lyα photons are re-emitted from a large Lyα halo\(^{27,28}\) that is too faint to significantly affect current observations.
Fig. 2.— Comparison between models of cosmological infall and observed quasar spectra. The upper panel considers the redshift $4.795 \pm 0.004$ quasar SDSS 1122-0229$^3$; based on the observed redshift and continuum level our model implies a $4.6 \times 10^8 M_\odot$ black hole residing in a $2.5 \times 10^{12} M_\odot$ host halo. The lower panel considers the redshift $6.28 \pm 0.02$ quasar SDSS 1030+0524$^4$, for which our model implies a $1.9 \times 10^9 M_\odot$ black hole residing in a $4.0 \times 10^{12} M_\odot$ host halo (we do not use a second spectral observation of this same source$^{29}$ since it appears to have a significantly lower signal-to-noise ratio). In each panel, the histogram shows the observed spectrum, the dashed line shows previous models that assume a uniform expanding universe, and the solid line shows our model which includes cosmological infall as well as a realistic distribution of gas clumps. Note that the velocity is measured relative to the quasar, where negative velocity means motion towards us. In each panel, the vertical dotted line shows the position of the Ly$\alpha$ wavelength at the source redshift, and the horizontal dotted line shows the flux level of the highest transmission peaks seen in parts of the spectrum corresponding to the average intergalactic medium (i.e., at velocities more negative than -4000 km s$^{-1}$). We assume an intrinsic emission line given by a sum of two Gaussian components, a form which best fits the line shape of most quasars at low redshift$^{30}$; we fix the parameters for each quasar based on the unabsorbed part of the Ly$\alpha$ line at velocities above 500 km s$^{-1}$. With this approach the models do not include any free parameters. Particular quasars are expected to show fluctuations around our predicted absorption profile, since our model averages over random lines of sight and density fluctuations. Throughout this paper we assume the standard cosmological parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.05$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $n = 1$. 