QUASARS PROBING QUASARS. III. NEW CLUES TO FEEDBACK, QUENCHING, AND THE PHYSICS OF MASSIVE GALAXY FORMATION

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Received 2008 June 3; accepted 2008 September 10; published 2008 December 22

ABSTRACT

Galaxies hosting \( z \sim 2 \) quasars are the high-\( z \) progenitors of today’s massive “red and dead” galaxies. With close pairs of quasars at different redshifts, a background quasar can be used to study a foreground quasar’s halo gas in absorption, providing a wealth of information about feedback, quenching, and the physics of massive galaxy formation. We present a Keck/High Resolution Echelle Spectrometer spectrum of the bright background quasar in a projected pair with angular separation \( \theta = 13.3 \text{ arcsec} \) corresponding to \( R_1 = 108 \text{ kpc} \) at the redshift of the foreground quasar \( z_{fg} = 2.4360 \pm 0.0005 \), precisely determined from Gemini/Gemini Near-Infrared Spectrograph near-IR spectroscopy. Our echelle spectrum reveals optically thick gas (\( N_{HI} \approx 10^{19.7} \text{ cm}^{-2} \)) coincident with the foreground quasar redshift. The ionic transitions of associated metal lines reveal the following properties of the foreground quasar’s halo: (1) the kinematics are extreme with absorption extending to \( +780 \text{ km s}^{-1} \) relative to \( z_{fg} \); (2) the metallicity is nearly solar; (3) the temperature of the predominantly ionized gas is \( T \lesssim 20,000 \text{ K} \); (4) the electron density is \( n_e \sim 1 \text{ cm}^{-3} \) indicating a characteristic size \( \sim 100 \text{ pc} \) for the absorbing “clouds”; (5) there is little (if any) warm gas \( T \lesssim 10^4 \text{ K} \); (6) the gas is unlikely illuminated by the foreground quasar, implying anisotropic or intermittent emission. The mass of cold \( T \sim 10^4 \text{ K} \) gas implied by our observations is significant, amounting to a few percent of the total expected baryonic mass density of the foreground quasar’s dark halo at \( r \sim 100 \text{ kpc} \). The origin of this material is still unclear, and we discuss several possibilities in the context of current models of feedback and massive galaxy formation.

Key words: galaxies: formation – intergalactic medium – quasars: absorption lines – quasars: general

Online-only material: color figures

1. INTRODUCTION

Over the course of a quasar’s lifetime, the accretion of material onto its \( \sim 10^9 M_\odot \) supermassive black hole will liberate an enormous energy \( E = \epsilon M_{BH} c^2 \sim 2 \times 10^{62} \text{ erg} \) affecting its environment from pc to Gpc scales. On cosmological scales, the collective emission from quasars dominates the ultraviolet (UV) background radiation field (Haardt & Madau 1996) that maintains roughly 90% of the universe as a highly ionized plasma (Gunn & Peterson 1965), while the harder photons produce the cosmic X-ray background (Fabian & Iwasawa 1999; Elvis et al. 2002; Ueda et al. 2003; Cao 2005). On Mpc scales, the UV flux photoionizes the nearby intergalactic medium (IGM) resulting in the proximity effect, or the lower optical depth for Ly\( \alpha \) absorption at the quasar redshift (Bajtlik et al. 1988; Scott et al. 2000). On the smallest scales of 1–100 pc, the interplay between black hole accretion, radiation, and the surrounding gas produces the characteristic emission from the well studied broad and narrow emission-line regions (see Osterbrock & Ferland 2006).

But the degree to which a quasar can influence its host galaxy on scales \( \sim \text{kpc} \) \( \sim \text{Mpc} \) is much less clear. Indeed, just a few percent of the energy \( \sim 10^{52} \text{ erg} \) emitted by a quasar is comparable to the binding energy of a massive galaxy \( \sim 10^{60} \text{ erg} \), and thus capable of ejecting its interstellar medium (ISM) or shock heating it to temperatures \( T \sim 10^7 \text{ K} \). The bulges of all local galaxies harbor supermassive black holes (Kormendy & Richstone 1995), the masses of which are tightly correlated with the properties of their host spheroids, measured on scales \( \sim \text{kpc} \) (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000). This has led many to speculate that some “feedback” mechanism couples the quasar phase of rapid supermassive black hole growth with the evolution of its host galaxy (e.g., Silk & Rees 1998; Kauffmann & Haehnelt 2000; Wyithe & Loeb 2003; Grant et al. 2004; Scannapieco & Oh 2004; Springel et al. 2005a; Scannapieco et al. 2005; Kawata & Gibson 2005; Menci et al. 2006; Cox et al. 2006; Lu & Mo 2007; Sijacki et al. 2007; Hopkins et al. 2008b).

Besides explaining the correlation between black holes and bulges, feedback from an active galactic nucleus (AGN) has also been invoked on even larger scales, as the energy source which “quenches” star formation in massive galaxies, leaving them “red and dead.” The observed bimodality in the galaxy color–magnitude diagram (Strateva et al. 2001; Baldry et al. 2004; Bell et al. 2004; Blanton et al. 2005; Faber et al. 2007) and the sharp cutoff at the bright end of the galaxy luminosity function (Benson et al. 2003) both point to some physical mechanism which shuts off star formation in massive galaxies. Otherwise, large quantities of gas should have accreted onto the progenitors of ellipticals resulting in an unseen population of very massive blue galaxies. It is generally believed that the coupling between the quasar and the galaxy is “kinetic” in nature, involving galactic scale outflows which suppress gas accretion and inject heat, ultimately shutting off star formation (e.g., Kauffmann &...
An important laboratory for studying the astrophysics of quasar feedback and quenching are luminous high-redshift radio galaxies (HzRGs; for a review see McCarthy 1993; Miley & De Breuck 2008). In these sources outflowing collimated relativistic plasma, or “radio jets,” can extend to several tens of kpc from the optical host galaxies, providing the most compelling evidence that an AGN can impact its galactic scale surroundings. It is unclear, however, whether this jet energy $\gtrsim 10^{60}$ erg (e.g., Miley 1980) couples strongly to the ambient ISM (Begelman & Cioffi 1989). In addition to the tremendous radio power, $z \gtrsim 2$ HzRGs are often associated with giant Lyα recombination nebulae, with sizes of up to $\approx 200$ kpc, sometimes extending well beyond the radio emission (see Villar-Martín et al. 2007 for a review). Ionizing radiation from the central AGN, thought to be obscured from our vantage point, is likely to play a significant role in exciting this emission. But the extreme kinematics of these nebulae (FWHM $\gtrsim 1000$ km s$^{-1}$; Nesvadba et al. 2006; Reuland et al. 2007; Villar-Martín et al. 2007), their complex irregular morphology, the tendency for the line emission to be aligned with the axis of the radio jets, and their near solar metallicities (Vernet et al. 2001; Humphrey et al. 2008) strongly suggest that jet–gas interactions or feedback from the AGN is giving rise to a large-scale outflow, and shocks from these motions could also be triggering the emission. But the comoving number density of HzRGs and giant Lyα nebulae, $n \sim 10^{-3}$ Mpc$^{-3}$ (Miley & De Breuck 2008), is about three orders of magnitude smaller than the number density of luminous quasars. Thus, only about one in a thousand of the supermassive black holes in the universe exhibits such dramatic evidence for feedback during their active phase, which would do little to quench star formation in the entire population of local massive galaxies. Is feedback occurring in the typical quasar in the universe?

While it has been argued that heating from a quasar is responsible for quenching massive galaxies (Springel et al. 2005b; Hopkins et al. 2007a), an alternative scenario is related to the physics of structure formation in a hierarchical universe. This idea goes back to a classic argument first made by Rees & Ostriker (1977) that the ability to cool on a dynamical timescale is what sets the upper bound for the mass of luminous galaxies. Thus, only about one in a thousand of the supermassive black holes in the universe exhibits such dramatic evidence for feedback during their active phase, which would do little to quench star formation in the entire population of local massive galaxies. Is feedback occurring in the typical quasar in the universe?

In a series of papers, we have introduced a novel technique to study the physical state of gas in the ISM and halo of luminous quasars, which has the potential to provide powerful constraints on feedback, quenching, and the physics of massive galaxy formation. Namely, we use a background quasar (b/g quasar) sightline to probe the state of gas in absorption in the vicinity of a foreground quasar (f/g quasar; see also Bowen et al. 2006). Although such projected quasar pair sightlines are extremely rare, Hennawi et al. (2006b; see also Hennawi et al. 2004) showed that it is straightforward to select $z \gtrsim 2$ projected quasar pairs from the imaging and spectroscopy provided by the Sloan Digital Sky Survey (SDSS; York et al. 2000). To date, about 90 pairs of quasars have been uncovered with impact parameter $R < 300$ kpc and $z_{\text{fg}} > 1.6$. Spectroscopic observations of the b/g quasar in each pair reveal the nature of pressure-confined (and thus long lived) gas clumps ($M \sim 10^5$–$10^8 M_\odot$) form, which can penetrate the halo and deliver the necessary heat.

Understanding the role that quasar feedback, hot halos, cold accretion, and pressure-confined clumps play in quenching star formation requires studying the physical state of the gas on scales 10 kpc–1 Mpc in the high-redshift progenitors of local massive red galaxies. Conroy et al. (2008; see also Wechsler et al. 1998) model the clustering and number density of $z \sim 2$–3 star-forming galaxies and deduced host dark halo masses $M \lesssim 10^{13} M_\odot$. These low masses allowed them to convincingly argue that $z \sim 2$–3 star-forming galaxies do not evolve into the quenched red and dead galaxies that we see today, but rather evolve into blue $\sim L_*$ galaxies similar to the Milky Way. But the strong clustering of luminous quasars at $z \sim 2$ implies larger dark halo masses $\gtrsim 10^{13} M_\odot$ (Croom et al. 2001; Porciani et al. 2004; Croom et al. 2005), indicating that they are indeed the progenitors of local red and dead galaxies. Of course, we are only observing a small fraction $\sim 10^{-2}$ to $10^{-3}$ of these progenitors as quasars at any given time because the quasar lifetime is much shorter than the age of the universe.

However quasar spectra have thus far provided little insight into the state of gas in their galactic environments for two reasons. First, the large ionizing flux from the quasar typically photoionizes the hydrogen in and around the galactic host (Hennawi & Prochaska 2007; Prochaska et al. 2008b; Chelouche et al. 2008), which would otherwise be detected as strong H$\alpha$ absorption at the quasar redshift. Second, the interpretation of material that is detected in absorption along the line of sight to a quasar is limited by the unknown distance between the material and the quasar. A systematic search for the signatures of photoionized gas near quasars (e.g., via N$\alpha$, O$\alpha$ absorption) is only now being carried out on statistical data sets (Tripp et al. 2008; Fox et al. 2008). Observers do frequently identify narrow associated absorption lines (NAALs) or so-called “associated absorbers,” which are believed to arise in the quasar environment. Some of these are attributed to gas on sub-pc scales (e.g., Elvis 2000), but other examples exhibit ionization states that suggest the gas lies at several tens of kpc (D’Odorico et al. 2004; Rix et al. 2007). Note that these associated absorbers are distinct from the broad absorption-line (BAL) features which arise from dense clumps of material that have been ionized and accelerated by the quasar, and are generally believed to be confined to sub-kpc scales (but see de Kool et al. 2001).

6 Because the implied lifetime of the jets and nebulae is $\sim 10^8$ yr, they cannot represent a short lived phase of evolution in every quasar.

7 The lower limit on redshift is motivated by the ability to detect redshifted Lyα absorption above the atmospheric cutoff $\lambda > 3200$ Å.
of the IGM transverse to the f/g quasar on scales of a few 10 kpc to several Mpc. This approach has the advantage of tracing diffuse gas over a wide range of density and temperature, ranging from cold neutral material $T \approx 10^4$ K to collisionally ionized plasma $T \approx 10^7$ K, and with column densities in the range $N \sim 10^{12} - 10^{22}$ cm$^{-2}$. In Paper I (Hennawi et al. 2006a), we searched 149 b/g quasar spectra for optically thick absorption in the vicinity of $1.8 < z_{fg} < 4.0$ luminous f/g quasars, and uncovered a sample of 27 new quasar–absorber pairs with impact parameters ranging from 30 kpc to 2.5 Mpc. In Paper II (Hennawi & Prochaska 2007), we analyzed the clustering of these transverse absorbers with the foreground quasar and measured a large clustering signal on galactic scales. We also refer the reader to the manuscript by Tytler et al. (2007) who consider several applications of quasar pair spectroscopy.

In this paper, we present the first high-resolution spectrum of the b/g quasar in the close projected quasar pair SDSSJ1204+0221. By mining the sky for very rare close associations of quasars (Hennawi 2004; Hennawi et al. 2006b, 2006a), we previously discovered this rare system with angular separation $\theta = 13.3$ arcsec corresponding to impact parameter $R_\perp = 108$ kpc at the redshift of the foreground quasar $z_{fg} = 2.436 \pm 0.0005$, precisely determined from Gemini/Gemini Near-Infrared Spectrograph (GNIRS). The spectral and photometric properties of SDSSJ1204+0221FG make it an unremarkable quasar at $z \sim 2.4$. We estimate a bolometric luminosity of $L_{\text{QSO}} \simeq 1.4 \times 10^{46}$ erg s$^{-1}$ placing it near the “knee” of the $z \sim 2.5$ quasar luminosity function (Croom et al. 2004; Richards et al. 2006), and corresponding to a supermassive black hole $M_{\bullet} \simeq 1.1 \times 10^5 (L_\odot / M_\odot)^{-1}$ if it accretes at one-tenth of the Eddington limit. The impact parameter of our background sightline $R_\perp = 108$ kpc easily resolves the expected virial radius $r_{\text{vir}} = 250$ kpc ($M/10^{13.3} M_\odot)^{1/3}$ of the f/g quasar host, and pierces its halo at about the “cooling radius”, where gas shock-heated to the virial temperature should take about a Hubble time to cool. The only remarkable thing about SDSSJ1204+0221 is that it has a $z_{bg} = 2.53$ b/g quasar in close projection which is bright enough ($r = 19.0$) for high-resolution spectroscopy. Our Keck/High Resolution Echelle Spectrometer (HIRES) of SDSSJ1204+0221BG, the first ever to probe the halo gas of a f/g quasar, resolves the velocity fields of the absorbing gas and allows us to measure precise column densities for H i and theionic transitions of metals like Si, C, N, O, and Fe. These measurements allow us to place constraints on the physical state of the gas near the f/g quasar, such as its kinematics, temperature, ionization structure, chemical enrichment patterns, volume density, the size of the absorbers, the intensity of the impinging radiation field, as well as test for the presence of hot collisionally ionized gas. In Section 2, we present the observations and provide column density measurements. We constrain the ionization state, estimate relative chemical abundances, and constrain the electron density of the gas in Section 3. In Section 4, we further discuss our results and how they relate to other observations of quasars, absorption-line systems, and high-redshift galaxies. The implications of our results for models of feedback, quenching, and massive galaxy formation are presented in Section 5, and we conclude with a summary in Section 6. The reader who is not concerned with the details of the observations and absorption-line modeling can read Table 4 summarizing those results and then skip to Section 4. Throughout the manuscript, we use the cosmological parameters $\Omega_m = 0.30$, $\Omega_{\Lambda} = 0.70$, $h = 0.70$, consistent to within $1 - \sigma$ with the parameters measured by the Wilkinson Microwave Anisotropy Probe (WMAP) experiment (Dunkley et al. 2008) and we adopt the solar chemical composition compiled by Grevesse et al. (2007).

2. OBSERVATIONS AND ANALYSIS

The principal goal of our analysis is to search for and characterize gas associated with the foreground quasar SDSSJ1204+0221FG in the high-resolution spectrum of a background quasar SDSSJ1204+0221BG identified in close projection. To establish a physical association, we demand that the absorption and SDSSJ1204+0221FG have nearly identical velocity. To this end, we must obtain precise measurements for the quasar systemic redshift. But, it is well known that the primary rest-frame UV emission lines which are redshifted into the optical for $z \gtrsim 2$ quasars can differ by up to $\sim 3000$ km s$^{-1}$ from systemic, due to outflowing/inflowing material in the broad-line regions of quasars (Gaskell 1982; Tytler & Fan 1992; Vanden Berk et al. 2001; Richards et al. 2002), with a more typical error being $\sim 1000$ km s$^{-1}$. An accurate redshift can be determined from narrow (σ $\lesssim 200$ km s$^{-1}$) forbidden emission lines, such as [O ii] $\lambda 3727$ or [O iii] $\lambda 5007$ which arise from the narrow-line region, but at $z \gtrsim 2$, measurements of these lines require spectra covering the near infrared.

To this end we observed SDSSJ1204+0221FG using the GNIRS (Elia et al. 2006) on the Gemini-South telescope on 2006 March 27. We used the 0.15/pixel camera and the 32 lines mm$^{-1}$ grating in a cross-dispersed mode, giving complete coverage over the wavelength range 0.9–2.4 μm. The slit width was 0.45 (∼ 3 pixels) giving a resolving power of $R \approx 1100$ or a FWHM $\approx 270$ km s$^{-1}$. The total exposure time was 5440 s, which was broken up into 16 × 340 s exposures to prevent the brightest sky lines from saturating the detector. The GNIRS spectra were reduced using standard techniques with a custom data reduction pipeline written in the Interactive Data Language (IDL) and described in J. F. Hennawi & J. Prochaska (2009, in preparation). Wavelength solutions were determined by comparing extracted spectra of the night sky to an atlas of OH sky emission lines, and heliocentric corrections were applied to the spectra. The rms deviation in our wavelength fits was typically 1–1.5 Å (or about 0.2–0.3 pixels). In the H band, this corresponds to a velocity uncertainty of 20–30 km s$^{-1}$, but since our fits typically use 50 lines, we believe that our wavelength solutions are accurate to better than $\lesssim 5$ km s$^{-1}$.

We computed a systemic redshift from the strong [O iii] $\lambda 5007$ emission line$^8$ which is redshifted to $\sim 1.7$ μm in the H band for $z \sim 2.4$ (see Figure 1). We found that the most effective line-centering algorithm was to iterate a flux-weighted line-centering scheme until the line center converged to within a specified tolerance. We achieved more stable results when the pixel values were weighted by a Gaussian kernel (true flux weighting would correspond to a box-car kernel) with dispersion set to σ[O iii] = 6.04 Å, which is the average dispersion of the [O iii] emission line measured by Vanden Berk et al. (2001). We do not estimate formal errors for the line centering, as they are smaller than the intrinsic error incurred by using [O iii] as a proxy for the systemic frame. Boroson (2005) measured the distribution of velocity shifts of the [O iii] line center about the systemic frame defined by low-ionization forbidden lines. He found that [O iii] has an average blueshift of $\Delta v = 27$ km s$^{-1}$ from systemic and a dispersion of $\sigma = 44$ km s$^{-1}$ about this value. To account for

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$^8$ The [O iii] 4959 line is plagued by sky emission lines and the Hβ lines are not as reliable a diagnostic as [O iii] for QSO redshifts.
the average shift, we add \( \Delta v = 27 \text{ km s}^{-1} \) to the vacuum rest wavelength of 5008.24 Å when computing the redshift of the line. For the 1σ error on our [O iii] near-IR redshifts we adopt \( \sigma = 44 \text{ km s}^{-1} \). We thus determine the systemic redshift of SDSSJ1204+0221FG to be \( z_{\text{fg}} = 2.4360 \pm 0.0005 \). All velocities are reported relative to this redshift value for the remainder of this paper. Figure 1 shows part of the H-band region of our GNIRS spectrum of SDSSJ1204+0221FG centered on the H\( \beta \)-[O iii] emission-line complex (H\( \beta \) \( \lambda \)4861, [O iii] \( \lambda \)4959, and [O iii] \( \lambda \)5007) and our determination of the systemic redshift.

High-resolution optical spectroscopy of the b/g quasar SDSSJ1204+0221BG was obtained on the nights of UT 2005 April 13 and 2005 May 3 (one 2400 s exposure per night), using the HIRESb spectrometer (Vogt et al. 1994) on the Keck I telescope. The data were acquired through the C5 dekker affording a FWHM \( \approx 8 \text{ km s}^{-1} \) resolution and processed with the HIRedux pipeline (R. Bernstein et al. 2008, in preparation). The signal-to-noise ratio (S/N) per 2.6 km s\(^{-1}\) pixel is approximately 15 at 4000 Å and the combined spectrum offers nearly continuous wavelength coverage from \( \lambda \approx 3450 \) to 6400 Å. A search for gas in the spectrum of SDSSJ1204+0221BG at \( z \approx z_{\text{fg}} \) revealed a strong Ly\( \alpha \) profile and a series of metal-line transitions. In Figure 2, we present the Ly\( \alpha \) and Ly\( \beta \) profiles for this absorption system. One readily observes the damping wings of the Ly\( \alpha \) profile which require a total H\( i \) column densities to be \( N_{\text{HI}}^{A,C} \approx 10^{19} \text{ cm}^{-2} \); larger values give a damped Ly\( \alpha \) (DLA) profile that contradicts the observed fluxes at \( \lambda \approx 4177.5 \) and 4187.5 Å (i.e., \( \delta v \approx -100 \text{ km s}^{-1} \) and +750 km s\(^{-1}\) in Figure 2). Similarly, the Ly\( \beta \) profile demands effective Doppler parameters \( b_{A,C} \approx 25 \text{ km s}^{-1} \). Allowing for these constraints, we derive a value of \( N_{\text{HI}}^{B} = 10^{19.07^{+0.15}_{-0.13}} \text{ cm}^{-2} \) for subsystem B that is independent of its nearly unconstrained Doppler parameter. The error in this \( N_{\text{HI}}^{B} \) estimate includes uncertainty due to the continuum placement and line blending with subsystems A and C. In the figure, we have overplotted a best-fit solution which assumes \( N_{\text{HI}}^{B} = 10^{18.6} \text{ cm}^{-2} \) for the subsystems A and C.

In Figure 3 we present a subset of the metal-line transitions observed along the sightline near the redshift of the foreground quasar. All velocities are relative to the redshift of SDSSJ1204+0221FG, \( z_{\text{fg}} = 2.4360 \). The various ions observed near this redshift show absorption in roughly three distinct velocity intervals spanning a total interval \( \Delta v \approx 650 \text{ km s}^{-1} \). We define these three velocity intervals as “subsystems”, A: \( +50 \text{ km s}^{-1} < \delta v < +200 \text{ km s}^{-1} \); B: \( +200 \text{ km s}^{-1} < \delta v < +600 \text{ km s}^{-1} \); and C: \( +600 \text{ km s}^{-1} < \delta v < +750 \text{ km s}^{-1} \). We have measured column densities for the ions observed in these subsystems with two methods: (1) by fitting Voigt profiles to the metal-line profiles show these subsystems are the blend of several narrow components but we only consider a single H\( i \) cloud for each. Therefore, the \( b \)-values reported for the H\( i \) gas likely overestimate the values of the individual components.

\( ^{9} \) http://www.ucolick.org/~xavier/HIRedux/index.html
the data using the VPFIT software package (kindly provided by R. Carswell); and (2) by integrating the apparent optical depth profile (AODM; Savage & Sembach 1991). The Voigt-profile fitting is most reliably performed on unsaturated transitions of ions which show similar velocity structure. In this case, one can “tie” the redshifts of the components which comprise the velocity profile for all of the ions analyzed and only allow the column densities and Doppler parameters to vary. The VPFIT software package minimizes the χ² of the profile fits and reports a best value of the redshift, b-value, and column density for each component introduced by the user.

We were able to employ the Voigt-profile procedure on the majority of low and intermediate ions for subsystems A and C. With the exception of Si IV in subsystem C, however, we could not recover a consistent solution assuming the same component structure for the low and high ions. Therefore, we calculate the high-ion column densities using the AODM method integrated across the entire velocity interval of each subsystem. We conclude that the high-ion gas arises in a distinct phase with a unique velocity field. In the ionization modeling that follows (Section 3), one should keep in mind that the subsystems are likely multiphase absorbers. This means the resulting high-to-low-ion ratios should be considered upper limits with respect to the nature of the lowest ionization phase. The results of the line-profile fits are overplotted in Figure 3 and tabulated in Table 1.

The velocity profiles of subsystem B are more complicated than subsystems A and C. This complex absorption precludes a well constrained line-profile solution based on individual Voigt profiles. Furthermore, it is apparent from a visual inspection of the Si II and C IV transitions that the ratios of the low- to high-ion columns vary significantly from δv ≈ +300 to +500 km s⁻¹. Therefore, subsystem B comprised gas in at least two different ionization phases. This includes the most highly ionized gas on the sightline (at δv ≈ +430 km s⁻¹), where one observes strong C IV and Si IV absorption but very little O I or Si II gas. For subsystem B, therefore, we report total column densities based on the AODM and caution that an analysis of the gas properties must consider multiphase material.

### 3. Ionization Modeling and Physical Conditions

In this section we constrain the ionization state of the gas in the three subsystems identified with the super-LLS identified at z ≈ 2.4360 toward SDSSJ1204+0221BG, named SLLS/SDSSJ1204+0221BG. One goal is to test the hypothesis that the nearby quasar SDSSJ1204+0221FG is shining on the gas. A test of this hypothesis is to compare the intensity of the ionizing radiation field that reproduces the observed ionic ratios with the predicted flux of the quasar at the impact parameter of the sightline. We constrain the intensity by comparing observed ionic ratios with photoionization models. Another goal is to constrain the chemical abundances of the gas. These measurements reflect the integrated star formation history of the galaxy that hosts (or hosted) the absorber and, in turn, star formation in this quasar environment. Standard practice is to gauge the contributions of Type II nucleosynthesis relative to Type I abundances from estimates of the α/Fe ratio where α-elements include O, Mg, Si, and S. The data also constrain the N abundance which is expected to trace nucleosynthesis by intermediate-mass stars and therefore offer unique constraints on the timescales of star formation (Henry et al. 2000; Henry & Prochaska 2007). This requires an assessment of the ionization state to estimate corrections to the observed ionic ratios.

The analysis focuses on multiple ionization states of individual elements (e.g., N⁺/N⁺, Si⁺/Si⁺²) to avoid uncertainties related to intrinsic abundances. For an optically thick absorber, one expects absorption from ions with ionization potentials (IPs) of one to a few Ryd. Ions with lower IPs should be absent because H I gas is essentially transparent to photons with energies less than 1 Ryd. Photons with energies above a few Ryd will be significantly attenuated by the H I gas and for hν > 4 Ryd by helium. Our analysis is most sensitive to the shape and intensity of the radiation field at 1 to 4 Ryd, although the nature of the radiation field at higher energies is constrained by observations

### Table 1: Voigt Profile Solutions

| Comp | z   | σ(z) (10⁻²) | v° (km s⁻¹) | b (km s⁻¹) | Ion | log N (cm⁻²) | σ(N) |
|------|-----|-------------|-------------|------------|-----|--------------|------|
| H I  | A   | 2.43744     | H I         | 18.60      | 0.40|
|      | B   | 2.44000     | H I         | 19.60      | 0.15|
|      | C   | 2.44367     | H I         | 18.60      | 0.40|

| Metals |
|--------|
| C II  | 1  | 2.437010     | 1.0         | +88        | 12.22| 7.77          | N II | 12.84 | 0.80|
|       | 2  | 2.437150     | 1.0         | +100       | 60.71| 15.80         | N II | 13.87 | 0.14|
|       | 3  | 2.437451     | 0.2         | +127       | 4.49 | 0.31          | N II | 13.09 | 0.06|
|       |    |              |             |            |      |               | N II | 14.84 | 0.22|
|       |    |              |             |            |      |               | O I  | 14.60 | 0.06|
|       |    |              |             |            |      |               | Al II| 12.97 | 0.13|
|       |    |              |             |            |      |               | Si II| 14.07 | 0.11|
|       |    |              |             |            |      |               | Fe II| 13.26 | 0.08|
|       | 4  | 2.437664     | 0.5         | +145       | 5.82 | 0.86          | N II | 12.46 | 0.27|
|       |    |              |             |            |      |               | N II | 13.82 | 0.05|
|       |    |              |             |            |      |               | O I  | 13.28 | 0.12|
|       |    |              |             |            |      |               | Al II| 11.92 | 0.06|
|       |    |              |             |            |      |               | Si II| 13.23 | 0.05|
|       |    |              |             |            |      |               | Fe II| 12.40 | 0.50|
|       | 5  | 2.443318     | 0.6         | +639       | 5.48 | 0.60          | C n* | 13.00 | 0.09|
|       |    |              |             |            |      |               | N I  | 13.75 | 0.05|
|       |    |              |             |            |      |               | O I  | 14.62 | 0.06|
|       |    |              |             |            |      |               | Al II| 12.29 | 0.07|
|       |    |              |             |            |      |               | Si II| 13.65 | 0.05|
|       |    |              |             |            |      |               | Si IV| 12.05 | 1.40|
|       |    |              |             |            |      |               | Fe II| 12.82 | 0.19|
|       | 6  | 2.444947     | 1.3         | +655       | 9.05 | 2.83          | C n* | 12.94 | 0.13|
|       |    |              |             |            |      |               | N I  | 13.46 | 0.11|
|       |    |              |             |            |      |               | O I  | 14.22 | 0.16|
|       |    |              |             |            |      |               | Al II| 12.26 | 0.09|
|       |    |              |             |            |      |               | Si II| 13.38 | 0.11|
|       |    |              |             |            |      |               | Si IV| 12.76 | 0.35|
|       |    |              |             |            |      |               | Fe II| 12.66 | 0.31|
|       | 7  | 2.443702     | 0.2         | +672       | 4.35 | 0.27          | C n* | 13.35 | 0.04|
|       |    |              |             |            |      |               | N I  | 14.33 | 0.05|
|       |    |              |             |            |      |               | O I  | 15.35 | 0.12|
|       |    |              |             |            |      |               | Al II| 12.57 | 0.09|
|       |    |              |             |            |      |               | Si II| 14.12 | 0.08|
|       |    |              |             |            |      |               | Si IV| 12.20 | 1.32|
|       |    |              |             |            |      |               | Fe II| 13.16 | 0.09|
|       |    |              |             |            |      |               | O I  | 13.74 | 0.21|
|       |    |              |             |            |      |               | Al II| 11.36 | 0.14|
|       |    |              |             |            |      |               | Si II| 12.76 | 0.09|

Note. a Velocity relative to the redshift of the foreground quasar SDSSJ1204+0221FG, z₁₀ ≈ 2.4360.

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11 Even in this case, a reasonable fit required a substantially different Doppler parameter.
Figure 3. Metal-line transitions from the SLLS identified at the redshift of SDSSJ1204+0221FG. The velocities are relative to the measured redshift of SDSSJ1204+0221FG, $z_{fg} = 2.4360$. The absorption occurs in three velocity intervals which we designate as subsystems A, B, C as denoted by the vertical dashed lines in the upper panel of each subplot. Note the strong low ion and N\textsc{ii} absorption, the absence of Si\textsc{ii}∗ 1264, the relatively weak C\textsc{iv} and Si\textsc{iv} profiles, and the likely absence of N\textsc{v} and O\textsc{vi} absorption. For a subset of the transitions from subsystems A and C we overplot the line-profile fits derived using the VPFIT software package and mark the components included (dark blue) and not included (light red) in the fit as listed in Table 1. Absorption that is presumed unrelated to SLLS/SDSSJ1204+0221BG (e.g., Ly\textsc{α} features from unrelated redshifts) is presented as a dashed, orange line. (A color version of this figure is available in the online journal.)

of N\textsc{v} and O\textsc{vi} transitions: IP(N+4) = 77.4 eV and IP(O+5) = 113.9 eV.

Finally, we will constrain the electron density $n_e$ of the gas by comparing the relative populations of the $J = 3/2$ and $1/2$ fine-structure levels of C\textsc{+} and Si\textsc{+} ions (e.g., Prochaska 1999; Silva & Viegas 2002). We will argue the gas is partially ionized and therefore assume collisions by electrons\footnote{The impact parameter of SDSSJ1204+0221BG from SDSSJ1204+0221FG is sufficiently large that indirect UV pumping by SDSSJ1204+0221FG does not contribute to the excitation of these lines.} dominate excitation to the $J = 3/2$ upper level. With an estimate of the gas temperature one estimates $n_e$ by measuring the relative populations of the ground and excited states.

In the following subsections, we start with the simpler subsystems A and C before considering the more complex subsystem B.

3.1. Subsystem A: $+50 \text{ km s}^{-1} < \delta v < +200 \text{ km s}^{-1}$

Before delving into detailed photoionization models, one can build intuition by making qualitative inspection of the ions detected. Examining subsystem A in Figure 3, one notes strong...
absorption from a series of low ions, e.g., O\textsuperscript{0}, Si\textsuperscript{+}, N\textsuperscript{0}, Fe\textsuperscript{+}. This is characteristic of Lyman limit systems where the large H\textsc{i} opacity self-shields gas from local or background UV sources. Elements therefore occupy the first ionization state (termed the low ion) with an IP greater than 1 Ryd. One also identifies strong N\textsc{ii} absorption that traces the observed N\textsc{i} profile in subsystem A. The measured ratio of these ionization states is large, \( \log[N(N^+)/N(N^0)] = +1.8 \) dex, revealing that the gas is partially ionized. On the other hand, there is only weak Si\textsc{iv} and C\textsc{iv} absorption at these velocities indicating the ionization state of the gas is not extreme. Furthermore, the absence of strong N \textsc{v} and O \textsc{vi} absorption at these velocities limits the flux of photons with energies \( hv \geq 4 \) Ryd and also rules out a collisionally ionized gas with \( T \approx 10^7 \) K (see Section 4.4). Qualitatively, the data suggest a partially ionized gas with \( T < 10^5 \) K.

There are two main mechanisms that produce a partially ionized gas: collisional ionization and photoionization. Under the assumption of collisional ionization equilibrium (CIE; Sutherland & Dopita 1993), the detection of low ions like O\textsuperscript{0} and N\textsuperscript{0} requires the electron temperature to be \( T_e < 30,000 \) K. This constraint is supported by the small for the N\textsc{ii} gas at \( T \) to the intensity of the ionizing radiation field. Finally, because following photoionization modeling, we will, however, assume motions, we can set a 2\( \sigma \) upper limit to the temperature \( T_e < 25,000 \) K. We achieve a similar limit by fitting the N gas and Si gas independently at the same redshift and use the difference in Doppler parameters to estimate \( T_e \). Nevertheless, a CIE model with \( T_e \approx 25,000 \) K does roughly reproduce the observed ionization ratios of Si\textsuperscript{+}/Si\textsuperscript{+3}, Al\textsuperscript{+}/Al\textsuperscript{+3}, and Fe\textsuperscript{+}/Fe\textsuperscript{+3} with N\textsuperscript{+}/N\textsuperscript{0} discrepant (the model underpredicts this ratio). Therefore, one cannot rule out a model where collisional ionization is the primary mechanism producing the observed ionized ratios, although to invoke this scenario one must introduce a heat source to maintain the gas at this temperature because the cooling time is short (cool \( \lesssim 10^4 \) yr) for any reasonable density. In the following photoionization modeling, we will, however, assume that photoionization is dominant and thereby set an upper limit to the intensity of the ionizing radiation field. Finally, because the gas is partially ionized one presumes that \( T_e > 10,000 \) K. In the following and throughout the remainder of the paper we will adopt an electron temperature \( T_e = 20,000 \) K.

To explore photoionization, we have used the Cloudy software package (Ferland et al. 1998) to calculate the ionization state of plane-parallel slabs with total column density log \( N_{\text{H}1} = 18.6 \), density \( n_{\text{H}} = 0.1 \) cm\textsuperscript{-3}, and metallicity [M/H] = −0.5, while varying the ionization parameter \( U = \Phi/n_{\text{H}} \) where \( \Phi \) is the flux of ionizing photons having \( hv \geq 1 \) Ryd. The results are largely insensitive to this choice of volume density (they are nearly homologous with \( U \)), but they do vary with metallicity because this affects the cooling rate of the gas and the electron density. We will demonstrate that the assumed metallicity is consistent with the [O/H] value inferred from the observed O\textsuperscript{0}/H\textsuperscript{0} ratio. For the calculations, we assume a power-law spectrum \( f_{\nu} \propto \nu^{-1.57} \) which is representative of z ≈ 2 quasars (Telfer et al. 2002). The results are nearly identical if we instead use the extragalactic UV background (EUVB) field computed by Haardt & Madau (1996) because the radiation fields have very similar slopes at the energies that span the IPs of the observed ions (\( hv = 1−3 \) Ryd). When the input \( U \) parameter is varied, the algorithm varies the number of gas slabs to maintain a constant \( N_{\text{H}1} \) value. Because subsystem A is optically thick, the results are sensitive to the assumed \( N_{\text{H}1} \) value; unfortunately, this quantity is not well constrained by the observations (Section 2). Larger \( N_{\text{H}1} \) values imply more self-shielding of the inner regions which, in turn, demand a more intense radiation field to explain the observed ionization states. The various ions respond differently to the shielding effects and pose an independent constraint on the \( N_{\text{H}1} \) value under the assumptions of this photoionization model. For example, we cannot reproduce the observed Fe\textsuperscript{+}/Fe\textsuperscript{+3}, Si\textsuperscript{+}/Si\textsuperscript{+3}, and N\textsuperscript{0}/N\textsuperscript{+} ratios when \( N_{\text{H}1} > 10^{19} \) cm\textsuperscript{-2}; the N\textsuperscript{0}/N\textsuperscript{+} ratios require \( \log U = -2 \) while the other two ratios set an upper limit \( \log U < -3 \). Under the assumption of a single-phase photoionization model with \( f_{\nu} \propto \nu^{-1.57} \), the data require \( N_{\text{H}1} < 10^{18.75} \) cm\textsuperscript{-2} with a preferred value of \( N_{\text{H}1} \approx 10^{18.6} \) cm\textsuperscript{-2}. This central value is consistent with the line-profile analysis of Ly\( \alpha \) and Ly\( \beta \) for subsystem A (Figure 2).

Figure 4 presents the results of the Cloudy calculations for a series of ionic ratios for a wide range of ionization parameters assuming \( N_{\text{H}1} = 10^{18.6} \) cm\textsuperscript{-2}. As noted above, we examine multiple ionization states of the same element (e.g., N\textsuperscript{0}/N\textsuperscript{+}) to provide constraints that are independent of intrinsic abundances. The observational constraints (Table 2) on the ionic ratios are indicated by vertical error intervals (or lower and upper limits) and the corresponding horizontal error intervals (or lower and upper limits) on \( \log U \) are indicated. One notes that even with this lower \( N_{\text{H}1} \) value, the constraints are not fully consistent with a single \( U \) value; in particular the observed N\textsuperscript{0}/N\textsuperscript{+} ratio indicates \( \log U > -3 \) whereas the other ratios imply \( \log U < -3 \). Although this inconsistency may suggest the low and intermediate ions arise in a multiphase or nonequilibrium medium, we caution that the systematic uncertainties inherent to photoionization modeling of optically thick absorbers are large (e.g., the assumed spectral shape, cloud geometry, and uncertain atomic data). In the following we will adopt an ionization parameter \( \log U = -3.0 \) dex with an uncertainty of 0.3 dex. This \( U \) value is similar to the results derived for other HLS at these redshifts (e.g., Prochaska 1999). It implies an ionization fraction \( x \equiv H^+/H = 0.96 \) and a total hydrogen column density \( N_{\text{H}} \equiv N_{\text{H}1}/(1-x) = 10^{20.8} \) cm\textsuperscript{-2} (\( N_{\text{H}1}/10^{18.6} \) cm\textsuperscript{-2}). Note that the error in \( 1-x \) is roughly linear with the uncertainty in \( U \) for \( \log U < -4 \) dex.

At low ionization parameters (\( \log U < -2.5 \); Figure 5), the O\textsuperscript{0}/H\textsuperscript{0} ratio is a good estimator of the oxygen abundance because the two atoms have very similar IPs and also because charge-exchange reactions mediate their ionization fractions. We calculate \( [O/H] = (\log O/H) - (\log O/H)_{\odot} = -0.65 - \log_{10}(N_{\text{H}1}/10^{18.6} \text{cm}^{-2}) \), assuming a solar oxygen abundance \( \log (O/H)_{\odot} = -3.34 \) dex. The uncertainty in this measurement (and any other chemical abundance measurements of subsystem A) is dominated by the poor constraint on the \( N_{\text{H}1} \) value. The Ly\( \alpha \) and Ly\( \beta \) profiles indicate \( N_{\text{H}1} < 10^{19} \) cm\textsuperscript{-2} which sets a lower limit to the metallicity of 1/10 solar abundance.

Relative abundance ratios (e.g., O/Fe) are less sensitive to the H\textsc{i} column density but are not strictly independent of \( N_{\text{H}1} \) because it dominates the opacity in our ionization models. Adopting \( \log U = -3 \) and \( \log N_{\text{H}1} = 10^{18.6} \) cm\textsuperscript{-2}, we find the following relative abundance values: [O/Fe] = +0.6 ± 0.1, [O/C] < +0.75, and [N/O] = −0.1 ± 0.2 dex (Table 3). The reported errors are dominated by uncertainty in the \( U \) parameter. We interpret these chemical abundance measurements in Section 4.2.

Independent of photoionization modeling, the data yield a measurement of the electron density from the observed populations of the fine-structure levels of Si\textsc{ii} and/or C\textsc{iii}. The
Table 2  
 Ionic Column Densities

| Ion  | \(\lambda_{rest}\) (Å) | \(\log f\) | \(v_{\text{max}}\) (km s\(^{-1}\)) | \(\log N_{\text{AODM}}\) | \(\log N_{\text{VPFIT}}\) |
|------|-----------------|---------|----------------|----------------|----------------|
| C\text{II} | 1036.3367 | -0.9097 | [37, 187] | >14.63 | |
| C\text{IV} | 1548.1950 | -0.7194 | [57, 227] | 13.60±0.03 | 13.60±0.03 |
| N\text{I} | 1242.8040 | -1.1066 | [87, 167] | <13.10 | |
| O\text{I} | 1031.9261 | -0.8765 | [67, 147] | 14.62±0.06 | |
| Al\text{III} | 1854.7164 | -0.2684 | [67, 187] | 13.01±0.12 | |
| Si\text{II} | 1264.7377 | -0.0441 | [37, 197] | 14.13±0.09 | |
| Al\text{III} | 1206.5000 | 0.2201 | [37, 217] | >13.66 | |
| Si\text{IV} | 1393.7550 | -0.2774 | [57, 187] | 19.32±0.03 | |
| Si\text{II} | 1402.7700 | -0.5817 | [57, 187] | 13.03±0.05 | |
| Fe\text{II} | 1122.5260 | -1.2684 | [67, 167] | <13.37 | |

Table 2 (Continued)  
 Ionic Column Densities

| Ion  | \(\lambda_{rest}\) (Å) | \(\log f\) | \(v_{\text{max}}\) (km s\(^{-1}\)) | \(\log N_{\text{AODM}}\) | \(\log N_{\text{VPFIT}}\) |
|------|-----------------|---------|----------------|----------------|----------------|
| C\text{II} | 1036.3367 | -0.9097 | [598, 698] | >14.79 | |
| C\text{IV} | 1548.1950 | -0.7194 | [568, 728] | 13.66±0.03 | |
| N\text{II} | 1550.7700 | -1.0213 | [568, 728] | 14.47±0.04 | |
| O\text{I} | 1083.9900 | -0.9867 | [598, 728] | <12.58 | |
| O\text{II} | 1242.8040 | -1.1066 | [618, 718] | <12.58 | |
| Al\text{III} | 1854.7164 | -0.2684 | [678, 818] | 15.46±0.09 | |
| Si\text{II} | 1264.7377 | -0.0441 | [628, 728] | 14.31±0.06 | |
| Si\text{III} | 1206.5000 | 0.2201 | [628, 728] | 13.59 | |
| Fe\text{II} | 1122.5260 | -1.2684 | [678, 778] | <13.37 | |

Notes.  
* Velocity interval for the AODM column density measurement. Velocities are relative to the redshift of the foreground quasar SDSSJ1204+0221FG, \(z_{\text{fg}} = 2.4360\).  
\(^{b}\)Sum of all fitted components.

Table 3  
 Elemental Abundances

| Ion  | \([X/H]\) | \([X/O]^{a}\) |
|------|---------|---------|
| Subsystem A\textsuperscript{a} | | |
| C\textsuperscript{I} | > -1.27 | > -0.65 |
| N\textsuperscript{I} | -0.65±0.14 | -0.03±0.08 |
| O\textsuperscript{I} | -0.62±0.06 | -0.40±0.25 |
| Al\textsuperscript{II} | -1.02±0.19 | -0.33±0.17 |
| Si\textsuperscript{II} | -0.95±0.11 | -0.64±0.05 |
| Fe\textsuperscript{II} | -1.26±0.03 | -0.38±0.05 |

Subsystem C\textsuperscript{b}

| C\textsuperscript{I} | > -1.10 | > -1.32 |
| N\textsuperscript{I} | 0.65±0.14 | 0.43±0.08 |
| O\textsuperscript{I} | 0.22±0.06 | 0.36±0.25 |
| Al\textsuperscript{III} | -1.14±0.19 | -1.36±0.25 |
| Si\textsuperscript{II} | -0.77±0.11 | -0.98±0.17 |
| Fe\textsuperscript{II} | -1.16±0.03 | -1.38±0.05 |

Note.  
* Assumes \(N_{\text{HI}} = 10^{18.6}\) cm\(^{-2}\) and \(U = -3.0\) ± 0.3 dex.

\(J = 1/2\) ground state of these ions has a corresponding \(J = 3/2\) fine-structure level which can be populated by collisions with ions and atoms, via indirect UV pumping, and also via a magnetic-dipole transition. For a partially ionized gas (demanded by the observed \(N_{\text{II}}/N_{\text{O}}\) ratio), collisions with free electrons should dominate excitation to the \(J = 3/2\)
Therefore, only the Si + levels (which have a wider energy discussion). Note that the constraints for C and Si are reported as upper limits. Indirect UV pumping could also contribute, but in subsystem A, the observations indicate log $U < -3.2$ for the C + excited level of C + are limited by the high ion absorption (C +3, Si +3) is likely associated with a different phase. The intensities for the EUVB and the foreground quasar at a distance of 100 kpc are shown on the top axis.

(A color version of this figure is available in the online journal.)

upper level. Indirect UV pumping could also contribute, but the quasars (foreground and background) are too distant and we assume that there are no important local sources (e.g., OB stars). In any case, contributions from UV pumping would only tighten the following upper limit on $n_e$. Unfortunately, the transitions from the $J = 3/2$ excited level of C + are blended with the resonant C + transitions of subsystem B. Therefore, only the Si + levels (which have a wider energy separation) are available for analysis. We set an upper limit to the relative populations based on the nondetection of the Si +1264 transition, log $[N(Si^{+3})/N(Si^{+1/2})] < -2.2$ dex. For a gas with $T_e \gg 413$ K, the level populations for excitation dominated by electron collisions is given by:

$$N(Si^{+1/2})/N(Si^{+3}) = \begin{cases} 1 & (T \gg 413 \text{ K}) \end{cases}$$

Adopting $T_e = 20,000$ K, the observations place an upper limit on the electron density, $n_e < 6 \text{ cm}^{-3}$.

One can use this constraint on the electron density to constrain the hydrogen volume density $n_H$ by assuming the ionization fraction from our photoionization model, i.e., $x = 0.96$. We calculate

$$n_H = n_e/x < 6.2 \text{ cm}^{-3}.$$  

One can also estimate a lower limit for the characteristic size of the system:

$$\ell = x \frac{N_H}{n_e} \left( 1 - x \right).$$

We derive $\ell > 5.2(3n_H/10^{18.6} \text{ cm}^{-2}) \text{ pc}$. $\ell > 5.2(3n_H/10^{18.6} \text{ cm}^{-2}) \text{ pc}$.

### 3.2. Subsystem C: $+600 \text{ km s}^{-1} < \delta v < +780 \text{ km s}^{-1}$

In comparison with subsystem A, we find similar results for the ionization state of subsystem C. These include strong N i absorption relative to N i which indicates a partially ionized gas. Again, a CIE model with $T_e \approx 20,000$ K yields ionization ratios consistent with the majority of observed ionization ratios, but we will focus on photoionization models of the gas. Like subsystem A, we also find that models with $N_{H1} < 10^{19} \text{ cm}^{-2}$ are preferred and the observed ion ratios (Fe +2/Fe +++, N +/N +, Si +/Si +3) imply $N_{H1} \approx 10^{18.6} \text{ cm}^{-2}$ and log $U < -3$. Using the same Cloudy model assumed for subsystem A, we derive the chemical abundances listed in Table 3.

In contrast to subsystem A, we measure larger metal column densities and a correspondingly higher oxygen abundance, $[O/ H] = +0.2 - \log 10(N_{H1}/10^{18.6} \text{ cm}^{-2})$, if the subsamples have comparable $N_{H1}$ values. Even if we have underestimated the H i column density of subsystem C by a factor of 0.5 dex (the maximum value allowed by the observed Lyα profile; Figure 2), the gas metallicity would be roughly solar. This lower limit ($[O/ H] > -0.25$) matches the highest values observed for DLAs (Prochaska et al. 2007) and all but a few super-LLS studied to date (Péroux et al. 2006; Prochaska et al. 2006). The data also suggest variations between the oxygen abundances of subsystems A and C (and also B, see below). Abundance variations like these are rarely studied in optically thick absorption-line systems because it is difficult to resolve the H i Lyman series (G. Prochter et al. 2008, in preparation).

The relative chemical abundances of O/Fe and N/O are also significantly higher in subsystem C than in subsystem A: $[O/ Fe] = +1.3 \pm 0.1$ dex, $[N/O] = +0.3 \pm 0.2$ dex. Although these values include ionization corrections (IC; Figure 5), the gas is indisputably α-enhanced and the N/O ratio must be greater than one half solar. This N/O value is unique for optically thick absorbers and the large α-enhancement also exceeds most measurements of O/Fe in extragalactic environments. We interpret these results further in Section 4.2.

We derive a constraint on the electron density of subsystem C from observations of fine-structure levels of C + and Si +. Assuming that excitation of the upper level is dominated by electron collisions, the populations of the excited state to the ground state for C + are related to the gas temperature and electron density, e.g.,

$$N(C^{+1/2}_{J=1/2})/N(C^{+3}_{J=3/2}) = \begin{cases} 1 & (T \gg 92 \text{ K}) \end{cases}$$

As for subsystem A, we assume $T_e = 20,000$ K, and obtain

$$n_e = \begin{cases} \frac{106}{N(C^{+3}_{J=3/2})/N(C^{+1/2}_{J=1/2}) - 1} & \end{cases}.$$  

Although the column density of the C +1/2 excited state is well constrained by the spectra, the resonance C +1036 and C +1334 transitions are heavily saturated. A conservative lower limit to $N(C^{+1/2}_{J=1/2})$ is derived by integrating the optical depth profile assuming a normalized flux equal to the 1σ error estimate, $N(C^{+1/2}_{J=1/2}) > 10^{14.8} \text{ cm}^{-2}$. Combined with our measurement of $N(C^{+3}_{J=3/2})$, we set an upper limit to the electron density $n_e < 3.5 \text{ cm}^{-3}$. Similar to subsystem A, we also derive an upper limit to $n_e$ from the nondetection of the Si + excited level, $n_e < 2.5 \text{ cm}^{-3}$ for $T_e = 20,000$ K (Equation 1). Assuming the same photoionization model (log $U = -3$, $x = 0.96$) as for subsystem A, we infer a hydrogen volume density $n_H < 2.6 \text{ cm}^{-3}$ and a lower limit to the characteristic size, $\ell > 15.5(3n_H/10^{18.6} \text{ cm}^{-2}) \text{ pc}$. $\ell > 15.5(3n_H/10^{18.6} \text{ cm}^{-2}) \text{ pc}$. 

Figure 4. Solid curves show predicted ionic ratios as a function of the ionization parameter $U$ for a series of ion pairs. These curves were calculated using the Cloudy software package assuming a plane-parallel slab of constant density material, a $f_\nu \propto \nu^{1.5}$ power-law spectrum, and solar relative abundances with an absolute metallicity $[M/H] = -0.5$ dex. Overplotted on the curves are observational constraints for subsystems A and C. With the exception of N/O and Fe/O in subsystem A, the observations indicate log $U < -3$ (see the text for a full discussion). Note that the constraints for C and Si are reported as upper limits to $U$ because the high ion absorption (C +3, Si +3) is likely associated with a different phase. The intensities for the EUVB and the foreground quasar at a distance of 100 kpc are shown on the top axis.

(A color version of this figure is available in the online journal.)
Because we have a positive detection for the C\textsuperscript{ii} 1335 transition, we may further constrain the volume density by estimating the total C\textsuperscript{+} column density from a proxy ion. A good choice is Si\textsuperscript{+} because our Cloudy calculations indicate Si\textsuperscript{+}/Si \approx C\textsuperscript{+}/C for log U \approx -3 d\text{ex}. This requires, however, that one adopt a value for the intrinsic Si/C ratio. If we assume solar relative abundances [Si/C] = 0, which is consistent with the C/Si ratio deduced from the ratio of C\textsuperscript{iV} to Si\textsuperscript{iV} assuming the IC of our best-fit photoionization model, we estimate log N(C\textsuperscript{+}) = 15.2 d\text{ex}. From Equation (4) we estimate \( n_e = 1.7\) cm\textsuperscript{-3}, which nearly matches the upper limit we have derived above. A more conservative estimate is to assume [Si/C] > -1 and report a lower limit to the electron density, \( n_e > 0.2\) cm\textsuperscript{-3}.

3.3. Subsystem B: +200 < \( \delta v < +600\) km s\textsuperscript{-1} 

As noted in Section 2, the velocity profiles of subsystem B are complex and preclude a well constrained solution using line-profile fitting techniques. Our expectation is that the velocity profiles comprised a series of overlapping components each with a line-profile similar to the components observed in subsystems A and C. With higher S/N data, one might be able to discern such structure. For now, we use the AODM to measure ionic column densities for this subsystem. This approach is problematic, however, for constraining the ionization state because the ionic ratios vary across the velocity profiles (e.g., N\textsuperscript{+}/N\textsuperscript{0} is significantly larger at \( \delta v = +470\) km s\textsuperscript{-1} than \( \delta v = +350\) km s\textsuperscript{-1}). Therefore, we cautiously report constraints on the ionization state and chemical abundances. We examine the integrated ionic column densities (and their ratios) which give optical depth weighted averages.

The integrated ionic column density ratios (e.g., N\textsuperscript{0}/N\textsuperscript{+}, Fe\textsuperscript{+}/Fe\textsuperscript{++}) in subsystem B are consistent with those observed for subsystems A and C. This suggests that the average ionization state of subsystem B is similar to that of subsystems A and C. Empirically, the low observed Fe\textsuperscript{+}/Fe\textsuperscript{++} and Al\textsuperscript{+}/Al\textsuperscript{++} ratios imply a modestly ionized gas with log U \approx -2.5 d\text{ex}, and the oxygen abundance should follow the O\textsuperscript{0}/H\textsuperscript{0} ratio: [O/ H] = -0.64 \pm 0.15 d\text{ex}. This value is lower than the O/ H abundance derived for subsystem C and suggests modest abundance variations exist between the subsystems. We also note that the observed O\textsuperscript{0}/Fe\textsuperscript{+} ratio for subsystem B requires at least a modest \( \alpha \)-enhancement, [O/Fe] > +0.4 d\text{ex} and that the observed N\textsuperscript{0}/O\textsuperscript{0} ratio implies [N/O] > -0.7 d\text{ex}. These values are similar to the results derived for subsystem A. For the remainder of the paper, we will adopt log U = -3.0 for this subsystem. Because this subsystem has a significantly higher N\textsubscript{H} value, this implies a higher neutral fraction (1 - \( x = 0.2\)) compared to subsystems A and C.

Finally, the nondetection of Si\textsuperscript{ii} 1264 absorption sets an upper limit to the electron density \( n_e < 2.5\) cm\textsuperscript{-3} under the assumption that electron collisions dominate the excitation rate and that \( T_e = 20,000\) K (Equation 1). If we assume the gas has an ionization fraction near unity, we set a similar upper limit for the hydrogen volume density and a size estimate \( \xi \approx 21\) pc.

4. DISCUSSION OF THE OBSERVATIONS 

In this section we discuss the observed properties of SLLS/SDSSJ1204+0221BG in terms of the galactic environment around high-z quasars. We examine the velocity field of this gas, examine its chemical abundances, and then test whether SDSSJ1204+0221FG may be shining on the absorbing material.

| Table 4 |
| --- |
| Summary of Properties for SLLS/SDSSJ1204+0221BG |
| Property | A | B | C |
| log (N\textsubscript{H}/cm\textsuperscript{-2}) | 18.6 \pm 0.4 | 19.60 \pm 0.15 | 18.6 \pm 0.4 |
| log U | -3.0 \pm 0.3 | -3.0 \pm 0.3 | -3.0 \pm 0.3 |
| \( T_e \) (K) | 4.3 \pm 0.15 | 4.3 \pm 0.15 | 4.3 \pm 0.15 |
| [O/ H\textsuperscript{+}] | -0.6 | -0.6 | +0.2 |
| log(O\textsuperscript{0}/Fe\textsuperscript{+})-log(O/Fe\textsuperscript{+}) | +0.1 | +0.5 | +0.8 |
| [O/ Fe\textsuperscript{+}] | +0.6 | +0.7 | +1.4 |
| log(N\textsuperscript{0}/O\textsuperscript{+})-log(N/O\textsuperscript{+}) | -0.6 | -0.7 | -0.1 |
| [N/O\textsuperscript{+}] | -0.0 | +0.5 | +0.4 |
| 1 - x | 0.04 \pm 0.01 | 0.18 \pm 0.05 | 0.04 \pm 0.01 |
| log(N\textsubscript{H}/cm\textsuperscript{-2}) | 20.00 | 20.34 | 20.00 |
| \( n_e \) (cm\textsuperscript{-3}) | +6.0 | <2.5 | 1.7\textsuperscript{+0.3} |
| \( N\textsubscript{H} \) (cm\textsuperscript{-3}) | <6.2 | <3.1 | 1.8\textsuperscript{-0.3} |
| \( \xi \) (pc) | >5.2 | >23.3 | 18.2 |

Notes. 

1. Oxygen metallicity estimated from the observed O\textsuperscript{0}/H\textsuperscript{0} ratio assuming no IC. Because IC would increase these values, one may consider them lower limits to the oxygen abundances subject to the large uncertainties in log N\textsubscript{H} for subsystems A and C.

2. Abundance derived from low-ion ratios and the IC calculated assuming log U = -3.0 \pm 0.3 d\text{ex}, N\textsubscript{H} as listed, [O/ H] = -0.5, and \( T_e = \xi v^{-1.57} \).

3. We estimate a log uncertainty of 0.8 d\text{ex} for Subsystems A and C where both N\textsubscript{H}, and x are uncertain and 0.4 d\text{ex} for subsystem B where the N\textsubscript{H} value is better constrained. A similar consideration holds for \( \xi \).

As our discussion focuses on a single system, the degree to which we can generalize these results is questionable. It is nevertheless fruitful to explore various scenarios for interpreting the observations. Table 4 summarizes the physical characteristics of SLLS/SDSSJ1204+0221BG derived in the previous section.

4.1. Kinematic Constraints

The most robust measurements for SLLS/SDSSJ1204+0221BG from our high-resolution spectrum of SDSSJ1204+0221BG are on the velocity field of the gas. Both the absolute (i.e., redshift) and relative velocities constrain the origin of the gas and its relation to the foreground quasar SDSSJ1204+0221FG. The redshift of SDSSJ1204+0221FG was measured from our observations of the rest-frame optical [O\textsubscript{III}] \( \lambda 5007\) emission line using the GNIRS spectrometer on the Gemini-S telescope (Section 2; Figure 1). We achieved a velocity precision of \( \approx 40\) km s\textsuperscript{-1} giving \( z_{fg} = 2.4360 \pm 0.0005\). Figures 2 and 3, which present the velocity profiles of SLLS/SDSSJ1204+0221BG relative to \( z_{fg} \), show strong H\text{I} and metal-line absorption from \( \delta v \approx +70\) to +700 km s\textsuperscript{-1}. These absorption profiles have two notable characteristics. First, the gas along the SDSSJ1204+0221BG sightline is asymmetrically distributed relative to \( z_{fg} \), i.e., within a 2000 km s\textsuperscript{-1} window centered on \( z = z_{fg} \), there is significant absorption only at \( z > z_{fg} \). The nearest “cloud” with \( T_{e, ave} > 1\) and \( \delta v < 0\) km s\textsuperscript{-1} lies off of Figure 2 at \( \delta v \approx -1500\) km s\textsuperscript{-1}, which corresponds to \( \approx 60\) h\textsuperscript{-1} Mpc (proper) under the assumption of Hubble expansion. Second, the total velocity width is very large, \( \Delta v \approx 650\) km s\textsuperscript{-1}. One may compare this value against the velocity widths measured for systems with comparable H\text{I} surface density, i.e., the DLAs and SLLSs. Regarding the former, the velocity width of SLLS/SDSSJ1204+0221BG exceeds greater than 99% of the \( \Delta v \) values for randomly selected DLAs at \( z > 2 \) (Prochaska & Wolfe 1997, 2001). Regarding the SLLS population (Péroux et al. 2003), none have as large a velocity width. The equivalent
width of the metal-line transitions (a proxy for velocity width) is also large compared with systems selected on the basis of metal-line absorption (e.g., the Mg 1568 PROCHASKA & HENNAWI 2004, 2005). In these respects, the velocity field of the gas near SDSSJ1204+0221FG is extreme.

Several factors lead us to conclude that the distance between the gas in SLLS/SDSSJ1204+0221BG and SDSSJ1204+0221FG is comparable to the impact parameter. Recall that SLLS/SDSSJ1204+0221BG exhibits a multicomponent kinematic structure with unusually large velocity width between the components. If the relative motions of the clouds and the quasar are to be interpreted as Hubble flow, their implied line-of-sight separation would be ≈ 2.8 Mpc (for Δt ≈ 700 km s⁻¹). The chance alignment of several galaxies across this large distance is unlikely, however, which we can quantify with clustering arguments. Quasars arise in highly biased regions of the universe. They are observed to cluster strongly on ∼ 10 h⁻¹ Mpc scales (Croom et al. 2001; Porciani et al. 2004; Croom et al. 2005; Myers et al. 2007a; Shen et al. 2008b) and the correlation function steepens considerably on smaller scales ∼ 100 h⁻¹ kpc (Hennawi et al. 2006b; Myers et al. 2007b, 2008). High-redshift quasars also exhibit a large cross-correlation amplitude with star-forming galaxies (Adelberger & Steidel 2005; Coil et al. 2007), and it is possible that galaxies clustered around the quasar are giving rise to the Lyα and metal-line absorption seen in SLLS/SDSSJ1204+0221BG. Another possibility is that the absorption in SLLS/SDSSJ1204+0221BG is not due to a nearby galaxy, but is rather halos gas distributed around the quasar with some density profile. Either scenario results in a clustering pattern around the quasar, which we measured in Hennawi & Prochaska (2007). The probability P(< r | R_L, v_max) that the total distance between the quasar and the absorber is less than r, given a fixed impact parameter R_L and the knowledge that absorption occurs within a velocity interval ±v_max, is simply an integral over this quasar–absorber correlation function.

Figure 6 shows this cumulative probability for v_max = 700 km s⁻¹ and the impact parameter of R_L = 108 kpc, from which we deduce that the probability for the gas in SLLS/SDSSJ1204+0221BG lying within 500 kpc of SDSSJ1204+0221FG is ≈ 70%. Perhaps an even stronger argument than r given a fixed impact parameter R_L and the knowledge that absorption occurs within a velocity interval ±v_max, is simply an integral over this quasar–absorber correlation function.

4.2. Clues from Chemical Enrichment

Clues to the origin of SLLS/SDSSJ1204+0221BG are encoded in the enrichment pattern of its gas. In particular, the alternative separations constrain the timescales and intensity of star formation of the galaxy (or galaxies) that produced the observed metals. Because the gas is partially ionized and we do not observe transitions from all ionization states, we proceed cautiously to interpret the observed ionic ratios. One robust conclusion from our abundance analysis (Section 3; Table 4) is the gas is highly enriched. The observed O⁹/H⁰ ratio indicates [O/H] > −1 across the ≈ 650 km s⁻¹ velocity interval spanning the entire system and we derive an integrated average abundance: [O/H]_TOT > −0.5 dex. This metallicity is expressed as a lower limit for several reasons. First, IC to the observed O⁹/H⁰ ratios will give larger [O/H] values (Figure 5). Second, the lower limit assumes the nearly maximal N_HI values permitted by the data for the three subsystems. If we adopt a modest IC and lower N_HI values, the oxygen metallicity for SLLS/SDSSJ1204+0221BG approaches the solar abundance. Finally, a proper derivation of the oxygen metallicity for the SLLS is to take an N_HI-weighted average of each subsystem. This is especially important for predominantly ionized gas. Using our fiducial values, we find < [O/H] > = −0.23 dex assuming no IC. We emphasize that even a 1/3 solar metallicity ([O/H] = −0.5 dex) represents a very high enrichment level. It exceeds the metallicity of nearly all optically thick absorbers at these redshifts: 98% of sightlines randomly intersecting galaxies (DLAs; Prochaska et al. 2003) and 95% of the super-LLS population (Péroux et al. 2007). Such high enrichment levels are generally observed only in gas within and around starburst galaxies (Pettini et al. 2002; Simcoe et al. 2006) and in quasar environments (Dietrich et al. 2003; D’Odorico et al. 2004; Arav et al. 2007).

The observations also constrain the relative abundances of O, Fe, and N, e.g., the O/Fe and N/O ratios. These diagnostics are valuable for constraining the star formation history for SLLS/SDSSJ1204+0221BG because each element is associated with a unique nucleosynthetic site and has a unique production timescale. Oxygen is made in massive stars and one predicts minimal delay (t < 100 Myr) for its nucleosynthesis and...
The first two examples reflect nucleosynthetic (Trager et al. 2000), and highly depleted ISM gas (e.g., Savage & Po- poor stars (e.g., McWilliam 1997), massive early-type galaxies high-

Figure 6. Probability distribution of the distance from the foreground quasar. The function \( P(< r | R_L, v_{\text{max}}) \) represents the probability that the distance from the foreground quasar is less than \( r \), given a fixed impact parameter \( R_L \) and knowledge that the absorber lies in the velocity interval \( \pm v_{\text{max}} \). The impact parameter for SDSSJ1204+0221 is used and a velocity interval of \( v_{\text{max}} = 700 \text{ km s}^{-1} \) was assumed. This probability is computed from the quasar-absorber correlation function \( \xi = 10(r/r_0)^{-\gamma} \) measured by Hennawi & Prochaska (2007), with \( \gamma = 2 \) and \( r_0 = 5.8 \text{ h}^{-1} \text{ Mpc} \). The solid (black) curve illustrates the probability distribution accounting for clustering with \( \xi \). The dashed (red) curve shows the probability if there is no clustering. The upper \( x \)-axis shows the ionizing photon flux \( \Phi_{\text{QSO}} \) implied by the SDSS magnitude of SDSSJ1204+0221FG at the given distance.

(A color version of this figure is available in the online journal.)

release to the ISM following the onset of star formation. The production of nitrogen and iron, however, is expected to be delayed by several 100 Myr to \( \approx 1 \text{ Gyr} \) because these elements are made in intermediate-mass stars and Type Ia Supernova (SN), respectively. By examining the relative abundances of O, N, and Fe, therefore, one may constrain the duration of the star formation episode that produced the metals.

Unfortunately, the relative abundance ratios of O, N, and Fe are more sensitive to the ionization state of the gas. The most conservative treatment is to report lower limits to \( \alpha/Fe \) and \( N/O \) from the observed ionic column density ratios of \( O/Fe^+ \) and \( N^0/Op^0 \). As with \( O^0/Op^0 \), corrections to these ionic ratios are positive definite (Figure 5). We measure lower limits to \( [O/Fe] \) of +0.1, +0.5, +0.8 dex for subsystems A, B, C, respectively, and conclude the gas has a super-solar \( \alpha/Fe \) ratio. For even a modest IC, the integrated average \( \alpha/Fe \) ratio approaches 10 times the solar ratio and exceeds the value measured for nearly all intervening absorption-line systems. In Figure 7, we present an estimate for these values for the various subsystems and also for the \( N_{\text{HI}} \)-weighted averages against measurements for a set of high-z galactic observations.

In the local universe, large \( \alpha/Fe \) ratios are observed in metal-poor stars (e.g., McWilliam 1997), massive early-type galaxies (Trager et al. 2000), and highly depleted ISM gas (e.g., Savage & Sembach 1996). The first two examples reflect nucleosynthetic enhancements and are attributed to the Type II supernovae (SNe) of massive stars. The latter example, however, results from the highly refractory nature of Fe relative to O, i.e., one observes enhanced \( O/Fe \) gas-phase abundances in the ISM because Fe is preferentially depleted into dust grains. The observed \( \alpha/Fe \) enhancement in SLLS/SDSSJ1204+0221BG could be due to one or both of these effects, but our expectation is that differential depletion is not dominant. A high depletion level would be unusual for gas with modest surface and volume densities that is predominantly ionized with a temperature of \( T \approx 20,000 \text{ K} \). It is more likely that the super-solar \( \alpha/Fe \) ratios reflect an intrinsic, nucleosynthetic enhancement. Granted the high metallicity of SLLS/SDSSJ1204+0221BG, the \( \alpha/Fe \) enhancement suggests a star formation history representative of bright spheroids (e.g., bulges, elliptical galaxies Graves et al. 2007). Chemical evolution modeling suggests these stellar systems underwent a short period of intense star formation where the gas was rapidly enriched by SNe from massive stars before Type Ia SN could contribute (e.g., Matteucci 1994). We conclude that the metals for SLLS/SDSSJ1204+0221BG were produced in a starburst lasting less than \( \approx 1 \text{ Gyr} \).

The \( N/O \) ratio of the gas offers additional constraints on the star formation history. Similar to \( O/Fe \), IC may be important and the conservative approach is to adopt the \( N^0/Op^0 \) ratio as a lower limit to \( N/O \). We find \( [N/O] > -0.7 \text{ dex for subsystems A and B and } [N/O] > -0.2 \text{ dex for subsystem C} \) (Table 4). The observations, specifically the large \( N^0/Op^0 \), indicate nonzero IC. We estimate the correction from photoionization modeling to be +0.25 to +0.5 dex for log \( U = -4 \) to −3 dex and conclude that \( N/O \) is at least 1/3 of the solar ratio in each subsystem and may be super-solar in subsystem C. These values are larger than \( N/O \) values observed for quasar absorption-line systems (Figure 7; e.g., Henry & Prochaska 2007). Indeed, solar \( N/O \) ratios are commonly observed only in quasar environments (Hamann & Ferland 1999; Dietrich et al. 2003; D’Odorico et al. 2004; Arav et al. 2007). This further reflects the high metallicity of SLLS/SDSSJ1204+0221BG because N behaves as a “secondary element” with its yield scaling as the square of the enrichment level \( (M/H)^2 \). Therefore, one expects near-solar or even super-solar \( N/O \) abundances in high-metallicity
environments. The exception to this expectation is if the system is too young for many intermediate-mass stars to have cycled through the asymptotic giant branch phase. The observation of nearly solar N/\O in SLLS/SDSSJ1204+0221BG, therefore, implies the gas was enriched over an episode of at least a few 100 Myr (Matteucci & Padovani 1993; Romano et al. 2002).

As noted above, the high metallicity and solar or super-solar N/\O and \alpha/\Fe ratios for SLLS/SDSSJ1204+0221BG describe a chemical abundance pattern that matches the abundances commonly measured for gas near quasars. This includes the high metallicities inferred from emission lines from the quasar broad-line region and the relative abundances derived for NAALs (Dietrich et al. 2003; D’Odorico et al. 2004). We are inclined, therefore, to causally connect the enrichment pattern of SLLS/SDSSJ1204+0221BG with SDSSJ1204+0221FG. A key question that follows is whether the metals were produced by the quasar’s host galaxy or whether they originated in a neighboring galaxy or galaxies. The latter hypothesis would imply that galaxies near quasars have enrichment histories similar to that inferred for the quasar environment, which could be tenable considering that early-type galaxies near the centers of modern clusters have very uniform colors and spectra indicating a common age of formation and star formation history (e.g., Bower et al. 1992). Alternatively, as we discuss further in the next section, the metals may have been generated during an early episode of star formation in the host galaxy of SDSSJ1204+0221FG, and then transported to large radii \(R_\perp \approx 100 \) kpc via a large-scale outflow in \( \approx 100 \) Myr time. To achieve a high N/\O ratio while maintaining a super-solar \alpha/\Fe ratio, the data suggest a starburst lasting several 100 Myr but less than \( \approx 1 \) Gyr. It is intriguing that the implied sequence of early, intense star formation followed by an optically bright quasar phase and possibly a large-scale outflow follows the general prescription for quasar activity proposed by Hopkins and collaborators (Springel et al. 2005a; Cox et al. 2006; Hopkins et al. 2008a).

4.3. Constraints from High-Ion Observations

The current paradigm of baryons within galactic halos envisions a hot, diffuse medium that has been heated by shocks during virialization and/or feedback from SNe within the galaxy. Embedded within this diffuse medium may be cooler, dense clouds that may be photoionized by the local or background UV radiation field. In the Galaxy, this simple picture is supported by the observations of the high-velocity clouds (cool, dense clumps, e.g.,; Wakker & van Woerden 1997; Putman et al. 2002) and the widespread detection of O\ Vi absorption which traces a hotter, diffuse medium (Sembach et al. 2003). This model is also supported by quasar absorption line surveys, i.e., the association of Mg\ II, C\ IV, and O\ Vi gas with galactic halos (e.g., Steidel 1993; Chen et al. 2001; Fox et al. 2007). On theoretical grounds, it has been argued that a hot diffuse component pressure confines a population of cold clouds, which are unlikely to be massive enough to be self-gravitating (Mo & Miralda-Escude 1996; Maller & Bullock 2004).

With these scenarios in mind, we are motivated to search for absorption from a diffuse, hot component that could be associated with the halo of SDSSJ1204+0221FG. The sightline to SDSSJ1204+0221BG intersects the presumed galactic halo of SDSSJ1204+0221FG at an impact parameter \(R_\perp = 108 \) kpc.

Figure 8. Apparent column density \(N_\alpha\) profiles for the NV 1242 transition, and the C\ IV and O\ Vi doublets for velocities relative to \(z_{fg} = 2.4360\). The profiles are significantly contaminated by coincident line blending which is best revealed by comparing the \(N_\alpha\) profiles for the pair of transitions in each doublet. After accounting for this line blending, we conclude that there is weak (or negligible) N\ V and O\ Vi absorption in subsystem C and at \(\delta v < 0 \) km s\(^{-1}\). Values and upper limits to the integrated ionic column densities are given in Table 5. (A color version of this figure is available in the online journal.)
As we will see in Section 5.1, the virial radius of the dark matter halo expected to host SDSSJ1204+0221FG is \( r_{\text{vir}} \approx 250 \text{ kpc} \), so that our background sightline easily resolves the virial radius. In Section 3, we discussed the detection and analysis of low and intermediate ion transitions observed in SLLS/SDSSJ1204+0221BG. We also commented on the general absence of strong absorption by high ions like O\(^{+5}\), C\(^{+3}\), and N\(^{+4}\). These ions trace gas either with a large ionization parameter (\( \log U > -2 \)) or with a high temperature (\( T > 10^5 \text{ K} \)). Their observed column densities, therefore, constrain the nature of a diffuse and/or hotter phase within the halo of SDSSJ1204+0221FG.

In Figure 8, we present the apparent column densities, \( N_{i}^{\alpha} \equiv 10^{14.5761} \ln(1/I^{\alpha})/(f \lambda) \), of the C\(^{+4}\), N\(^{+4}\), and O\(^{+5}\) profiles (smoothed by 5 pixels) for the velocity interval spanning the quasar redshift and the three subsystems of SLLS/SDSSJ1204+0221BG. The C\(^{+3}\) and O\(^{+5}\) ions exhibit multiple transitions which allow one to identify line blending by visual inspection, i.e., regions where the two profiles diverge significantly. The C\(^{+4}\) 1548 and 1550 profiles track each other closely for \( \delta v > +200 \text{ km s}^{-1} \) indicating a positive detection without blending at these velocities. At \( \delta v < +200 \text{ km s}^{-1} \), the profiles diverge because the C\(^{+4}\) 1548 profile of component C blends into the C\(^{+4}\) 1550 profile of component A (see also Figure 3). Therefore, the C\(^{+4}\) 1548 profile sets an upper limit to the column density of C\(^{+3}\) at these velocities. At \( \delta v \leq 0 \text{ km s}^{-1} \), there is no statistically significant detection of C\(^{+4}\).

The N\(^{+4}\) and O\(^{+5}\) doublets lie within the Ly\(\alpha\) forest and therefore are more likely to suffer from line blending. Examining the O\(^{+5}\) transitions, the two profiles diverge at nearly all velocities. This indicates that the line profiles are severely affected by blends, most likely Ly\(\alpha\) and Ly\(\beta\) absorption from gas at lower redshift. The only interval where the O\(^{+5}\) profiles roughly coincide is at 400 km s\(^{-1}\) < \( \delta v \) < 550 km s\(^{-1}\). One may optimistically interpret the absorption as a positive detection of O\(^{+5}\) ions, but the more conservative approach is to report even this absorption as an upper limit. Turning to N\(^{+4}\), we present only the N\(^{+4}\) 1242 transition because the N\(^{+4}\) 1238 profile is heavily blended with a strong Ly\(\alpha\) system at \( z = 2.502 \). We also expect that the broad absorption at \( \delta v < 200 \text{ km s}^{-1} \) is associated with coincident Ly\(\alpha\) absorption; meanwhile, the optical depth in subsystem C (\( \delta v < 600 \text{ km s}^{-1} \)) is not statistically significant. The only plausible N\(^{+4}\) absorption, therefore, is within subsystem B where one notes the optical depth profile of N\(^{+4}\) 1242 resembles that of C\(^{+4}\) in the interval 300 km s\(^{-1}\) < \( \delta v \) < 500 km s\(^{-1}\). We caution, however, that the O\(^{+5}\) profiles do not track N\(^{+4}\) in this velocity interval. This draws into question a positive detection of N\(^{+4}\) absorption because the O\(^{+5}\) and N\(^{+4}\) ions trace gas with similar physical properties and one generally expects coincident N\(^{+4}\) and O\(^{+5}\) absorption. It is possible, therefore, that the apparent N\(^{+4}\) profile instead tracks an unidentified blend and we report the measured optical depth as an upper limit to N\(^{+4}\) in subsystem B.

Table 5 summarizes the column densities of the high ions in subsystems A, B, and C and in the velocity interval containing \( z = z_{\text{fg}} \). For C\(^{+3}\) and N\(^{+4}\), the column densities are lower than \( 10^{14} \text{ cm}^{-2} \) and fall below \( 10^{13} \text{ cm}^{-2} \) in several regions. For O\(^{+5}\), the upper limits are a factor of 10 higher owing to noisier data and a higher frequency of line blending. All of these values lie below the \( \gtrsim 10^{14} \text{ cm}^{-2} \) column densities measured for the low ions of CNO in SLLS/SDSSJ1204+0221BG (Table 2). This has significant implications for the physical conditions of diffuse gas associated with the galactic halo of SDSSJ1204+0221FG.
The absence of photoionized high ions like O$^{+5}$ is not particularly surprising, however, because the ambient medium in the outer galactic halo surrounding a high-$z$ quasar almost certainly is at a temperature so high that collisional ionization dominates over photoionization. This material may be observed independently of the gas contributing to SLLS/SDSSJ1204+0221BG. A galaxy with mass $M > 10^{12} M_{\odot}$, for example, has an implied virial temperature in excess of $10^7$ K and the dark matter halo expected to host SDSSJ1204+0221FG would have a virial temperature $T_{\text{vir}} \sim 10^7$ K (see Section 5.1). In Figure 10 we present predicted column densities for C$^{+3}$, N$^{+4}$, and O$^{+5}$ ions assuming CIE (Sutherland & Dopita 1993). $N_{\text{H}} = 10^{21.8}$ cm$^{-2}$, and [M/H] = −0.5 dex. This H column density is the predicted value at $R_\perp = 108$ kpc in a $M = 10^{13.3} M_{\odot}$ halo with a Navarro–Frank–White (NFW) profile (concentration $c = 4$) and assuming a gas fraction $f_g = 0.17$ equal to the cosmic baryon fraction (Dunkley et al. 2008, see Section 5.1). The figure demonstrates that the gas must have $T > 10^6$ K to be consistent with the observed upper limits to $N(O^{+5})$. The dependence of $N(O^{+5})$ on $T$ is so strong that even if we assume considerably lower $N_{\text{H}}$ and [M/H] values for the diffuse component, the gas must have $T > 10^6$ K. A cooler phase is only allowed if log $N_{\text{H}} + [\text{M/H}] < 17.7$.

The principal conclusion of this section is that a diffuse medium in the halo of SDSSJ1204+0221FG must have a temperature exceeding $10^6$ K. This is consistent with the virial temperature $T_{\text{vir}} \sim 10^7$ K for the gas in the $M \gtrsim 10^{13} M_{\odot}$ dark matter halo that is expected to host the f/g quasar (see Section 5.1). Note, however, that the absence of strong high ion transitions associated with SDSSJ1204+0221FG contrasts with similar observations (using a b/g quasar sightline) of $z \sim 2.3$ star-forming galaxies where strong O vi and N v absorption is detected at similar impact parameters (Símcová et al. 2006). In addition, the damped Ly$\alpha$ systems (DLAs) also frequently exhibit O vi absorption which reflects a highly ionized, diffuse medium in the halos of these galaxies (Fox et al. 2007). The average $N(O^{+5})$ for the DLAs exceeds $10^{14}$ cm$^{-2}$. The DLA sightlines presumably intersect galactic halos at much smaller impact parameters than $R_\perp = 108$ kpc. Nevertheless, the high ion material in DLAs is undoubtedly associated with the galactic halo (Wolfe & Prochaska 2000; Maller et al. 2003; Prochaska et al. 2008a) and may extend to many tens kpc. The fundamental difference is that DLA sightlines will rarely penetrate the galaxies hosting high-$z$ quasars and likely trace lower mass halos with significantly lower virial temperatures.

![Figure 10](image-url)  
**Figure 10.** Predicted column densities for high-ion states of CNO and Si assuming CIE for a gas with total H column density $N_{\text{H}} = 10^{21.8}$ cm$^{-2}$ and 1/3 solar metallicity. This hydrogen column density corresponds to the estimated baryonic surface density at a 100 kpc impact parameter from a dark matter halo with $M = 10^{13} M_{\odot}$ and an NFW density profile. The arrows on the curves indicate constraints to the temperature based on upper limits to the observed ionic column densities. One notes that the data rule out $T > 10^6$ K. (A color version of this figure is available in the online journal.)

Of considerable interest to studies of quasars and the buildup of supermassive black holes in the universe (e.g., Yu & Tremaine 2002; Hopkins et al. 2007b; Shankar et al. 2007) is whether their optical–UV emission is isotropic and/or intermittent. Evidence that quasars emit anisotropically or intermittently comes from the null detections of the transverse proximity effect in the Ly$\alpha$ forests of projected quasar pairs (Croft 1989; Dobrzycki & Bechtold 1991; Fernandez-Soto et al. 1995; Liske & Williger 2001; Schirber et al. 2004; Croft 2004, but see Jakobsen et al. 2003), the anisotropic clustering of optically thick absorbers near quasars (Hennawi & Prochaska 2007; Prochaska et al. 2008b), and the absence of fluorescence detections in optically thick gas proximate to quasars (J. F. Hennawi & J. Prochaska 2009, in preparation; but see Adelberger et al. 2006). Together, these studies provide a statistical case that quasars emit anisotropically or intermittently.

For an individual quasar, one can use a background sightline to observe nearby gas in absorption, and test whether it is illuminated by studying its ionization state. The general approach is to (1) derive the ionization parameter $U$ of the gas near the quasar using ionic metal-line transitions, (2) estimate the volume density of the gas, and (3) compare the inferred intensity of the impinging radiation field with that estimated for the nearby quasar. Worseck et al. (2007) and Goncalves et al. (2008) have conducted this test for highly ionized gas near several $z \sim 2$ quasars. The Worseck et al. (2007) study was deemed inconclusive. Goncalves et al. (2008), meanwhile, identified several absorbers proximate to quasars with high ionization parameters and estimated an ionizing radiation field that exceeds the EUVB. Instead, the estimated fluxes roughly match the values calculated for the nearby quasars under the assumption that they emit isotropically. These authors, however, did not place empirical constraints on the gas density, did not consider the effects of collisional ionization, and did not explore the effects of nonsolar relative abundances. In these respects, we consider their results to be suggestive but inconclusive.

We can similarly test for illumination of SLLS/SDSSJ1204+0221BG by SDSSJ1204+0221FG. In Section 3, we compared the observed ratios of N, Si, Al, Fe, and C atoms and ions against photoionization models assuming a single phase, plane-parallel slab of gas illuminated by a quasar spectrum ($f_{\nu} \propto \nu^{-1.57}$). For subsystems A+C of SLLS/SDSSJ1204+0221BG, the majority of the observational constraints imply log $U < -3.25$. The only exception is the large N$^+$/N$^0$ ratio which indicates log $U \approx -3$ for subsystem A, and log $U > -4$ for subsystem C. Under the constraints of a single-phase model and a plane-parallel geometry, one cannot identify an equilibrium photoionization model that reproduces all of the observed ionized ratios. By the same token, the observations are inconsistent with any CIE model. We do not know if these inconsistencies highlight errors in the atomic data (e.g., dielectronic recombination rates), the oversimplification of a single-phase, plane-parallel geometry, an erroneous shape for the radiation field, and/or the presumption of equilibrium models. We will proceed under the relatively conservative assumption that the ionization parameter log $U < 1572$ PROCHASKA & HENNAWI  
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and we will comment on the implications for significantly smaller values. We also remind the reader that the observed ionic ratios are roughly consistent with a $T \approx 20,000$ K CIE model. Any contribution of collisional ionization processes to the observations would lower the estimated flux of ionizing radiation.

The other key physical constraint is the volume density of the gas $n_{\text{H}}$. For a predominantly ionized gas, this can be estimated from the electron density $n_e$. Our analysis of the fine-structure levels of the C$^+$ and Si$^+$ ions indicates $n_e$ less than approximately 5 cm$^{-3}$ for each of the subsystems. These upper limits could be improved by obtaining higher S/N observations of the undetected Si~II 1264 transition at $\lambda \approx 4350$ Å. In any case, we will adopt this conservative limit to the electron density and assume $n_{\text{H}} \approx n_e$, which is appropriate for a predominantly ionized medium.

Adopting $\log U < -3$ and $n_{\text{H}} < 5$ cm$^{-3}$, we infer an upper limit to the ionizing photon flux,

$$\Phi_{\text{obs}} = U n_{\text{H}} c < 1.5 \times 10^9 \text{ photons s}^{-1} \text{ cm}^{-2}. \quad (6)$$

We may compare this value with the ionizing flux of SDSSJ1204+0221FG under the assumptions that the gas lies at a distance equal to the impact parameter and that the quasar emits isotropically. Combining the SDSS optical photometry of SDSSJ1204+0221FG with an assumed power-law spectral shape ($f_\nu \propto \nu^{-1.57}$), we derive an AB magnitude $m_{912} = 21.42$ at 1 Ryd. At $z_{\text{fg}} = 2.436$, this gives a specific luminosity $L_{912} = 1.16 \times 10^{37}$ erg s$^{-1}$ Hz$^{-1}$ and we estimate an ionizing photon flux at $r = R_\perp = 108$ kpc of

$$\Phi_{\text{QSO}} = 9 \times 10^7 \text{ photons s}^{-1} \text{ cm}^{-2}, \quad (7)$$

assuming the quasar emits isotropically. Therefore, the conservative upper limit to $\Phi_{\text{obs}}$ roughly matches the predicted photon flux from SDSSJ1204+0221FG at the observed impact parameter. In this conservative observational limit, we do not have strong evidence for anisotropic emission.

If we adopt less conservative but more realistic constraints on the ionization parameter and volume density ($\log U < -4$; $n_{\text{H}} < 1$ cm$^{-3}$), we set an upper limit to the observed photon flux $\Phi_{\text{obs}} < 3 \times 10^9$ photons s$^{-1}$ cm$^{-2}$. To maintain the null hypothesis that SLLS/SDSSJ1204+0221FG is illuminated, we would require the gas to be located at $r > 500$ kpc. This large distance is disfavored by other arguments. The extreme velocity field, high metallicity, and quasar-like relative abundances suggest the gas is local to the quasar host galaxy. At $r = 500$ kpc, one could associate SLLS/SDSSJ1204+0221FG with a protocluster containing SDSSJ1204+0221FG, but not its galactic halo. Furthermore, the strong clustering of optically thick absorbers around quasars at $z \sim 2.5$ implies a high probability that $r \approx R_\perp$ (Hennawi & Prochaska 2007). In Figure 6, we show the probability of the absorber lying at a distance less than $r$ from the line of sight because this gas, which is by construction illuminated, is photoionized by the quasar. One test of this hypothesis is to search for an enhancement of highly ionized material along the sightline, e.g., Si IV, C IV, N v, O vi. Indeed, Wild et al. (2008) report a higher incidence of C IV absorption along the same sightlines where the lower IP transition, Mg ii, is deficient. There is also a high incidence of highly ionized absorbers within several thousand km s$^{-1}$ of the quasar redshift commonly termed NaAl systems (D’Odorico et al. 2004). We now explore the physical conditions required for SDSSJ1204+0221FG to photoionize/photovaporate SLLS/SDSSJ1204+0221FG and also the expected properties of SLLS/SDSSJ1204+0221FG if it were illuminated by the quasar, and thus exposed to a more intense radiation field. These calculations are similar to those performed by Chelouche et al. (2008) and we refer the reader to their work for additional analysis.

In Figure 9 we present a series of calculations from the Cloudy software package for constant density gas slabs placed 100 kpc from SDSSJ1204+0221FG along the sightline to Earth. The quasar’s specific luminosity was assumed to be a power law ($L_\nu \propto \nu^{-1.57}$) and was normalized to SDSS photometry: $L_\nu = L_{912}(\nu/912)^{-1.57}$ with $L_{912} = 1.16 \times 10^{30}$ erg s$^{-1}$ Hz$^{-1}$.
In all of the calculations we assume a gas metallicity \([\text{M}/\text{H}] = -0.5\) dex with solar relative abundances. In the upper panel of the figure, we show the \(\text{H}\) column densities as a function of the gas density \(n_{\text{H}}\). For slabs with \(n_{\text{H}} = 10^{19} \text{ cm}^{-2}\), the gas has \(N_{\text{H}} < 10^{17.2}\) and is hence optically thin to ionizing photons, provided \(n_{\text{H}} < 10^{-3}\); while slabs with \(n_{\text{H}} = 10^{21} \text{ cm}^{-2}\) are optically thin only if \(n_{\text{H}} < 0.1 \text{ cm}^{-3}\).

In Section 3, we estimated \(N_{\text{H}} \approx 10^{20} \text{ cm}^{-2}\) and \(n_{\text{H}} \approx 1 \text{ cm}^{-3}\) for subsystems A and C based on the relative column densities of several ion pairs, our estimate of the \(\text{H}\) i column density (uncertain by \(\pm 0.4\) dex), and an analysis of \(\text{C}\) ii and \(\text{Si}\) ii fine-structure transitions. According to the calculations presented in Figure 9, this gas would have \(N_{\text{H}} \approx 10^{17} \text{ cm}^{-2}\) if it were at 100 kpc from SDSSJ1204+0221FG along our sightline. If the volume density is just a little lower (permitted by the fine-structure analysis), the gas would be optically thin. We conclude that subsystems A and C of SLLS/SDSSJ1204+0221BG would be photoionized by SDSSJ1204+0221FG if it were placed along our sightline. Subsystem B, however, exhibits a larger \(N_{\text{H}}\) value, and has a larger implied \(N_{\text{H}} \approx 10^{20.4} \text{ cm}^{-2}\) value. Assuming \(n_{\text{H}} = 1 \text{ cm}^{-3}\), this system would have \(N_{\text{H}} \approx 10^{17.3} \text{ cm}^{-2}\) if illuminated by the SDSSJ1204+0221FG at a distance of 100 kpc. To be optically thin and illuminated at this distance requires \(n_{\text{H}} < 1 \text{ cm}^{-3}\). It is important to note that SDSSJ1204+0221FG is relatively faint compared to the brighter quasars studied to establish the low incidence of optically thick absorbers near quasars (e.g., Russell et al. 2006; Prochaska et al. 2008b; Wild et al. 2008). These quasars are a factor of \(\sim 5\)–10 brighter and the resulting ionization parameters are higher by the same factor. Thus, clouds with properties similar to SLLS/SDSSJ1204+0221BG could still appear optically thin if illuminated, resulting in no conflict with previous observations. Similarly, it would be very fruitful to characterize the incidence of proximate optically thick absorbers as a function of quasar luminosity.

If an absorber like SLLS/SDSSJ1204+0221BG is photoionized by a nearby quasar, the system may still give rise to several discernible features. If the \(\text{H}\) i column density exceeds \(10^{14} \text{ cm}^{-2}\), it would exhibit a strong Ly\(\alpha\) absorption feature. This would be difficult to distinguish from the ambient Ly\(\alpha\) forest, however. If this gas has even a modest metallicity, it may present the predicted column densities of several high ions as a function of the gas density.

Absorption systems with strong high ion absorption near quasars with \(z_{\text{abs}} \approx z_{\text{em}}\) or small velocity intervals \((\Delta v < 1000 \text{ km s}^{-1})\) have been detected in quasar spectra, and are referred to as NAAL systems (e.g., Wampler et al. 1993; Sri-anand & Petitjean 2000). The most comprehensive survey of these NAALs using high-resolution spectra was performed by D’Odorico et al. (2004) who analyzed the UVES key project of \(z \approx 2\) quasars. Of the 22 quasars in the sample, D’Odorico et al. (2004) report that 16 exhibit significant \(\text{C}\) iv absorption within \(\pm 5000 \text{ km s}^{-1}\) of \(z_{\text{em}}\) for a total of 34 \(\text{C}\) iv systems, 15 of which also exhibit \(\text{N}\) v absorption. D’Odorico et al. (2004) studied the properties of a subset which allowed for detailed photoionization modeling. The characteristics of this subset are similar in metallicity, density, and relative abundances to SLLS/SDSSJ1204+0221BG (see also Section 4.2). Furthermore, the authors used observed limits on the volume density of the gas (from fine-structure analysis) and estimates of partial coverage to infer distances of 10 to 200 kpc from the quasar. We conclude, therefore, that if SLLS/SDSSJ1204+0221BG experienced an \(\approx 10\) times higher ionization parameter, it would show characteristics common to NAAL systems. Indeed, SDSSJ1204+0221FG is approximately 2.5 mag (10\(\times\)) fainter than the quasars of the D’Odorico et al. (2004) sample. We speculate that an absorption line survey of intrinsically faint quasars will show a high incidence of absorbers with properties similar to SLLS/SDSSJ1204+0221BG and a correspondingly lower incidence of NAAL systems. One could perform such a survey with current and future echellette spectrometers on 10 m class telescopes.

5. NEW CLUES ABOUT MASSIVE GALAXY FORMATION

In this section we examine inferences one might draw from our measurements of SLLS/SDSSJ1204+0221BG in the context of galaxy formation models and quasar feedback. With only a single sightline, it is too early to draw firm conclusions on these processes. In part, the following section sets the framework for future discussion. We begin with a review of the expected properties of the dark matter halo for a \(z \approx 2\) quasar.

5.1. Expected Properties of SDSSJ1204+0221FG’s Dark Halo

Porciani et al. (2004) measured the clustering of quasars in the redshift range \(0.8 < z < 2.1\), which allowed them to estimate that quasars are hosted by dark matter halos with mass \(M \sim 10^{13} \odot\). As they found strong evolution of the clustering with redshift, which continues to even higher redshift \((z > 3.0\); see Shen et al. 2008b), we henceforth assume that SDSSJ1204+0221FG resides in a dark matter halo \(M = 10^{13.3} \odot\), but we caution that this mass is uncertain by a factor of \(\sim 0.5\) dex, due to both the measurement error and the intrinsic distribution of quasar host halo masses.

For a dark matter halo of this mass with an NFW profile (Navarro et al. 1997), the virial radius is

\[
r_{\text{vir}} = 251 \left( \frac{M}{10^{13.3} \odot} \right)^{1/3} \text{kpc}.
\]

Thus, if SDSSJ1204+0221FG resides at the center of its host dark matter halo, the SDSSJ1204+0221BG sightline probes it at \(\lesssim 50\%\) of the virial radius. If we assume a concentration parameter \(c = 4\) (characteristic of high-redshift halos), the peak
The circular velocity we deduce is comparable to the extreme kinematics observed in the subsystems of SLLS/SDSSJ1204+0221BG. It is thus conceivable that the motions in SLLS/SDSSJ1204+0221BG represent gravitational infall or virial motion of "cold gas clouds" orbiting in the dark matter halo potential, just as galaxies would. To make this more precise we note that the maximum extent spanned by the three components of SLLS/SDSSJ1204+0221BG is \( \Delta v \approx 650 \, \text{km s}^{-1} \). For a Gaussian distribution, we find that the maximum extent measured from three samples is related to the dispersion by\( \Delta v = 1.69 \sigma \), so we estimate that the dark matter halo host- ing SDSSJ1204+0221FG and SLLS/SDSSJ1204+0221BG has a line-of-sight velocity dispersion \( \sigma \approx 380 \, \text{km s}^{-1} \). Tormen (1997) found that the maximum circular velocity of an NFW halo is a factor of \( \approx 1.4 \) times larger than the maximum of the one-dimensional velocity dispersion, so our kinematics suggest \( v_{\text{circ}} = 540 \, \text{km s}^{-1} \). The velocity width of SLLS/SDSSJ1204+0221BG is consistent with the characteristic velocity for the dark matter halos hosting \( z \sim 2.5 \) quasars (Equation (9)), thus gravitational dynamics in the halo surrounding SDSSJ1204+0221FG could explain the observed kinematics. 

One challenge to this scenario is that the velocities of the clouds comprising SLLS/SDSSJ1204+0221BG are systematically offset to positive values relative to SDSSJ1204+0221FG. Such an offset is characteristic of organized motions (e.g., rotation, infall along a filament) rather than a random velocity field and we question whether a highly organized velocity field with large velocity width can occur in the outer halo. It is worth noting, however, that the offset resembles a similar trend observed for optically thick absorbers (Mg II systems) at \( z \sim 1 \). For these absorbers, Steidel et al. (2002) and Kapczynski et al. (2007) report a systematic velocity offset between the gas and the systemic velocity of its host galaxy. The origin of this asymmetry is not understood. Another explanation for the observed kinematics is that SLLS/SDSSJ1204+0221BG represents cold material swept up in large-scale outflow, which we consider in more detail in Section 5.4.

In the standard structure formation picture, gas falling into a massive dark matter halo will be shock-heated to near the virial temperature of the dark halo, converting its gravitational kinetic energy into thermal energy. The virial temperature is defined as

\[
T_{\text{vir}} = \frac{2 \mu m_p v_{\text{circ}}}{k_B} = 1.3 \times 10^{7} \left( \frac{M}{10^{13.3} M_\odot} \right)^{2/3} \text{K},
\]

where \( \mu \) is the mean atomic weight, which we take as \( \mu = 0.59 \) for a fully ionized primordial gas. Gas at these high temperatures will be collisionally ionized and should result in negligible H I absorption.

As we detect a large column of enriched and cold photoionized gas at \( T \approx 20,000 \, \text{K} \) in the background sightline, it is of interest to calculate the time that it would take gas shock-heated to the virial temperature to cool at the distance of our impact parameter. The cooling time of a gas is conventionally taken to be the ratio of its specific thermal energy to the volumetric cooling rate, or \( t_{\text{cool}} = [3(n_e + n_H) T] / [2 n_e n_H \Lambda] \), where \( \Lambda \) is the cooling function (e.g., Sutherland & Dopita 1993) and \( n \) is the total ion density. We can estimate the ion density of the quasar host halo assuming that the total mass (dark matter + gas) distribution follows an NFW density profile \( \rho(r) \), with the gas density being a fraction \( f_g \) of the total density \( \rho_{\text{tot}}(r) \). We then have \( n = \rho_g / \mu m_p \), or

\[
n(r = 108 \, \text{kpc}) \approx 7.5 \times 10^{-3} \left( f_g / 0.17 \right) \left( \frac{M}{10^{13.3} M_\odot} \right)^{0.73} \text{cm}^{-3},
\]

where we took \( f_g = \Omega_g / \Omega_m = 0.17 \) to be the cosmic baryon fraction from Dunkley et al. (2008). We finally find for the cooling time at \( r = 108 \, \text{kpc}, t_{\text{cool}} \approx 3.2 \times 10^6 (M/10^{13.3} M_\odot)^{-1/2} \) yr. Note that at the high virial temperatures \( T \sim 10^7 \, \text{K} \) characteristic of our dark matter halo, cooling is dominated by thermal bremsstrahlung radiation and hence does not depend strongly on metallicity. According to the current structure formation paradigm, the bulk of the gas interior to the virial radius should have been shock-heated to \( T_{\text{vir}} \), and the cooling time of this hot phase at \( R \approx 100 \, \text{kpc} \) is comparable to the age of the universe at \( z = 2.4360 \), \( t_{\text{cool}} = 2.6 \times 10^9 \) yr. Thus, the impact parameter \( R_{\perp} = 108 \, \text{kpc} \) for SDSSJ1204+0221BG probes SDSSJ1204+0221FG at approximately the cooling radius (where \( t_{\text{cool}} = t_{\text{t}} \), which is \( t_{\text{cool}} = 99 \, \text{kpc} \)). Furthermore, because the dynamical time (Equation (10)) is a factor of \( \sim 20 \) shorter than the cooling time, the dark matter halo we consider satisfies the condition for stable shock formation (Dekel & Birnboim 2006) and is in the pressure-supported "hot-halo" regime.

5.2. The Distribution of Cold Gas

From the foregoing discussion, we expect the bulk of the gas near SDSSJ1204+0221FG to have been shock-heated to the virial temperature of its hot-halo (see Equation (11)). However, our analysis of SLLS/SDSSJ1204+0221BG indicates a column density \( N_{\text{HI}} = 10^{19.68} \, \text{cm}^{-2} \), and hence a substantial amount of "cold" gas at \( R_{\perp} \approx 108 \, \text{kpc} \). Similarly, a high covering factor of high column density \( (N_{\text{HI}} > 10^{19} \, \text{cm}^{-2}) \) cold gas was seen statistically by Hennawi et al. (2006a) and Hennawi & Prochaska (2007). In what follows we combine the Hennawi & Prochaska (2007) measurement of the clustering of cold gas around quasars, with our measurements of the properties of SLLS/SDSSJ1204+0221BG (see Table 4), to estimate the covering factor, density, and volume filling factor of cold gas in the halos surrounding high-z massive galaxies.

At a transverse separation \( R_{\perp} \) from a foreground quasar, the covering factor of absorbers can be written (Hennawi & Prochaska 2007) as

\[
C(R_{\perp}) = \frac{\left[ \frac{dN}{dD} \right]}{[1 + \chi(R_{\perp}, \Delta D)] \Delta D},
\]

where we search over a radial (comoving) distance interval \( \Delta D \) corresponding to a redshift interval \( \Delta z \) in the background quasar spectrum. Here \( \left[ \frac{dN}{dD} \right] = n_{\text{abs}} A \) is the incidence of absorption line systems per unit comoving distance, which is simply the product of the comoving number density of the clouds which give rise to absorption line systems and their absorption cross-section \( A \) (in comoving units). The transverse correlation function
\(x_L(R, \Delta D)\) accounts for the enhancement due to clustering and can be written as an integral of the three-dimensional quasar–absorber correlation function, \(\xi_{QA}(r)\), over the search window (see Hennawi & Prochaska 2007 for details). Assuming a power-law shape for the quasar–absorber cross-correlation function, Hennawi & Prochaska (2007) measured \(r_0 = 9.2^{+1.5}_{-1.0} h^{-1}\) Mpc for \(\gamma = 1.6\), or \(r_0 = 5.8^{+1.0}_{-0.6} h^{-1}\) Mpc for \(\gamma = 2\). These fits imply covering factors of \(C(R_L = 108\text{ kpc}) = 0.29 \pm 0.08\) and \(0.53^{+0.13}_{-0.07}\), respectively. For this calculation we chose a projection distance \(\Delta D = 19.2\) Mpc along the line of sight, which corresponds to a velocity interval \(\pm 700\text{ km s}^{-1}\), motivated by the 650 km s\(^{-1}\) extent of the absorption components in SLLS/SDSSJ1204+0221BG.

For the simplified case of identical clouds of mass \(M_c\), the mass density of cold gas (in proper units) is

\[
\rho_{\text{cold}}(r) = \frac{1}{a^3} n_{\text{abs}} [1 + \xi_{QA}(r)] M_c
\]

\[
= \frac{1}{a} \left(\frac{dN}{dD}\right) [1 + \xi_{QA}(r)] N_H \frac{1}{X},
\]

where \(a\) is the scale factor, \(M_c\) is the mass of the clouds, \(X = 0.76\) is the hydrogen mass fraction, and \(\mu_c = 0.61\) is the mean atomic weight of the cold gas.\(^{15}\) Plugging in numbers using the parameters of SLLS/SDSSJ1204+0221BG we find

\[
\rho_{\text{cold}}(r = 108\text{ kpc}) \approx 3.0 \times 10^{-6} \left[\frac{108\text{ kpc}/r_0}{472}\right]^\gamma
\]

\[
\times \left(\frac{N_H}{10^{20.6} \text{ cm}^{-2}}\right) M_\odot \text{ pc}^{-3}.
\]

We can compare this to our expectation for the baryon density in an NFW halo at this distance (see Equation (12)), and thus compute the cold gas fraction

\[
\frac{\rho_{\text{cold}}(r = 108\text{ kpc})}{\rho_g} \approx 0.03 \left[\frac{f_g}{0.17}\right]^{-1} \left[\frac{108\text{ kpc}/r_0}{472}\right]^\gamma
\]

\[
\times \left(\frac{N_H}{10^{20.6} \text{ cm}^{-2}}\right) \left(\frac{M}{10^{13.3} M_\odot}\right)^{-0.73}.
\]

Unfortunately, this estimate suffers from a large uncertainty. Besides the \(0.5 \text{ dex}\) in the dark halo mass, the quasar–absorber correlation function has significant errors and an uncertain slope. Also we assumed a single cloud population with a total hydrogen column density \(N_H = 10^{20.6} \text{ cm}^{-2}\) equal to the total in SLLS/SDSSJ1204+0221BG. This value may not be representative of the cloud population near quasars as a whole, although the neutral column of SLLS/SDSSJ1204+0221BG \(N_{HI} = 10^{19.9}\text{ cm}^{-2}\) is lower than the average \((N_{HI}) \approx 10^{20.1}\text{ cm}^{-2}\) of the four absorbers with \(R < 200\text{ kpc}\) in the Hennawi & Prochaska (2007) clustering analysis. Finally, it is important to note that we have assumed a maximal value for the gas fraction, \(f_g = \Omega_b/\Omega_m = 0.17\), equal to the universal baryon fraction. While in principle the gas fraction can be this large, it is probably smaller because of gas loss from outflows. In this regard the cold gas fraction in Equation (15) could easily be a factor of \(\sim 2\) higher.

Despite the uncertainties, Equation (15) illustrates how measurements of the covering factor and column density distribution of optically thick absorbers combined with photoionization modeling, can be used to measure the cold gas density as a function of radius from massive dark halos. This new observable\(^{16}\) thus provides a direct test of ideas which are currently popular in structure formation models, such as the cooling radius, cold accretion, the formation of pressure-supported hot halos, and multiphase media (see below). Furthermore, although the current estimate crudely assumed that all gas clouds are the same as those in SLLS/SDSSJ1204+0221BG, a larger statistical analysis could use the distribution of cloud column densities measured from high-resolution spectra and photoionization modeling.

Next, we use our measurement of the electron density (see Section 3 and Table 4) and hence size of the absorbing clouds to determine their volume filling factor. The filling factor can be written as

\[
C_v(r) = \frac{1}{a^3} n_{\text{abs}} [1 + \xi_{QA}(r)] V_c = \frac{\left(\frac{dN}{dD}\right) [1 + \xi_{QA}(r)] N_H}{n_{HI}},
\]

where we used the fact that the ratio of the cloud volume to cloud area is the absorption path length \(V_c/(a^2A) = \ell = N_{HI}/n_{HI}\). Plugging in numbers we find

\[
C_v(r = 108\text{ kpc}) \approx 2.2 \times 10^{-5} \left[\frac{108\text{ kpc}/r_0}{472}\right]^\gamma
\]

\[
\times \left(\frac{N_{HI}}{10^{20} \text{ cm}^{-2}}\right) \left(\frac{n_e}{1.7\text{ cm}^{-3}}\right)^{-1},
\]

where we have used the \(\text{HI}\) cloud column and electron density measurements for component C (see Section 3). The mass of the clouds \(M_c \approx n_e \mu_c m_p (\ell/2)^3\), where \(n_e\) is the cold gas ion density and \(R_c\) is the cloud radius. For a hard sphere the cloud radius is related to the average absorption path by \(R_c = \ell/4\). Again, plugging in numbers for component C, we find

\[
M_c = 720 \left(\frac{N_{HI}}{10^{20} \text{ cm}^{-2}}\right)^3 \left(\frac{n_e}{1.7\text{ cm}^{-3}}\right)^{-2} M_\odot.
\]

However, we caution that this estimate is highly uncertain because of its dependence on large powers of quantities with significant errors.

Our conclusion from Equation (16) that a few percent of the total baryon supply is in a “cold” gas phase at \(T \sim 20,000\text{ K}\) implies that SDSSJ1204+0221FG has intercepted a multiphase medium. This is of particular interest in light of considerable theoretical work which indicates that the hot gas associated with massive galaxies should be thermally unstable and prone to fragmentation instabilities (Field 1965; Fall & Rees 1985; Murray & Lin 1990; Mo & Miralda-Escude 1996; Maller & Bullock 2004, but see Malagoli et al. 1990). The expected result of these instabilities is a fragmented distribution of cooled material at \(T \sim 10^4\text{ K}\), in pressure equilibrium with a hot gas background (Mo & Miralda-Escude 1996; Maller & Bullock 2004; Dekel & Birnboim 2006). These instabilities have not yet been seen in hydrodynamical simulations of galaxy formation (Katz 1992; Thoul & Weinberg 1995; Springel et al. 2001; Yoshida et al. 2002; Helly et al. 2003), which lack the mass resolution necessary to resolve them (Kaufmann et al. 2006). Some have suggested that the formation of this multiphase medium can dramatically influence galaxy formation, resulting

\(^{16}\) We note that previous works have studied the distribution of \(\text{HI}\) near star-forming galaxies (Adelberger et al. 2003, 2004; Simcoe et al. 2006), but these are significantly less massive galaxies \(M_{\text{ halo}} \sim 10^{11.5}\) and none estimated a cold gas density.
in a maximum galaxy mass in massive halos (Maller & Bullock 2004), or providing an important source of feedback energy (Dekel & Birnboim 2008).

To this end we compute the pressure \( P_c = n_e T_e \) of the cold clouds that we detect in absorption as SLLS/SDSSJ1204+0221BG to be

\[
P_c = 7.1 \times 10^4 \left( \frac{n_e}{1.7 \text{ cm}^{-3}} \right) \left( \frac{T}{20,000 \text{ K}} \right) \text{ K cm}^{-3}. \tag{20}
\]

This value can be compared to our estimate of the pressure in the NFW halo at \( r = 108 \) kpc thought to be hosting SDSSJ1204+0221FG, by combining equations (11) and (12),

\[
P_h \approx 9.8 \times 10^4 \left( \frac{f_{\xi}}{0.17} \right) \left( \frac{M}{10^{13} M_\odot} \right)^{1.4} \text{ K cm}^{-3}. \tag{21}
\]

It is compelling that these pressures are comparable. Our determination of the pressure of the absorbing gas in SLLS/SDSSJ1204+0221BG indicates that the gas clouds could very well be pressure confined by the hot \( T \sim 10^7 \text{ K} \) gas which is expected to permeate the dark matter halo of SDSSJ1204+0221FG.

5.3. Could the Absorbing Clouds be in Galaxies Clustered around the Quasar?

We can calculate the number density of the absorbing clouds from Equation (13) if we have knowledge of the absorption cross-section \( \chi \).

\[
n(r) = n_{\text{abs}}[1 + \xi_{\text{abs}}(r)] = \frac{C(R_{\odot})}{A\Delta D} \left( 1 + \xi_{\text{abs}}(r) \right) \frac{1 + \xi_{\text{abs}}(r)}{1 + \chi_{\perp}(R_{\odot}, \Delta D)}. \tag{22}
\]

We use our estimate for the radius of the absorber from component C, \( r_{\text{abs}} = 15 \) pc (see Section 3), to determine \( A = \pi r_{\text{abs}}^2 \). Combined with \( C(R_{\odot}) = 108 \) kpc from Hennawi & Prochaska (2007), Equation (22) gives for the number density

\[
n(r = 108 \text{ kpc}) = 3.7 \times 10^7 \text{ Mpc}^{-3} \left( \frac{C}{0.35} \right) \left( \frac{r_{\text{abs}}}{15 \text{ pc}} \right)^{-2} \times \left( \frac{1 + \xi_{\text{abs}}}{475} \right) \left( \frac{1 + \chi_{\perp}}{28} \right)^{-1}. \tag{23}
\]

This extremely high number density of clouds leads us to consider an alternative scenario where the small clouds we observe with characteristic size \( r_{\text{abs}} = 15 \) pc are organized in larger galactic structures (with characteristic size \( r_{\text{gal}} \)) which are clustered around the quasar. This scenario would still give rise to the small absorption path length of \( r_{\text{abs}} \sim 15 \) pc, but since the clouds are associated with galaxies the macroscopic absorption cross-section would be \( A_{\text{gal}} r_{\text{gal}}^2 \) and hence the implied number density of galactic hosts \( n_{\text{gal}} \) would be significantly smaller than determined from Equation (23). This scenario could also help explain why the metallicities deduced for SLLS/SDSSJ1204+0221BG are so high in spite of the large impact parameter \( R_{\perp} = 108 \) kpc from the quasar. If the absorbers are associated with nearby galaxies, then the characteristic size of these enriched regions would be \( r_{\text{gal}} \), obviating the need for the quasar to have transported the metals to large distances, perhaps via a large-scale outflow (see Section 5.4).

First, we assume the absorbers are as numerous as the faintest most abundant star-forming galaxies which have been studied to date and determine the corresponding size of the enriched regions. Reddy et al. (2008) calculated the luminosity function for a combined sample of brighter spectroscopic Lyman break galaxies (LBGs) and the fainter photometric LBGs from the Hubble Deep Field-North studied by Steidel et al. (1999). The comoving number density of the faintest star-forming galaxies at \( z \sim 3 \) is \( n_{\text{LBG}} = 6.9 \times 10^{-3} \text{ Mpc}^{-3} \) for a flux limit of \( M_{AB}(1700 \text{ Å}) < -18.2 \), corresponding to \( R < 26.9 \) or \( L > 0.09 L_\odot \). Adelberger & Steidel (2005) measured the clustering of LBGs around luminous quasars in the redshift range \( 2 \lesssim z \lesssim 3.5 \), and found a best-fit correlation length of \( r_0 = 4.7 h^{-1} \text{ Mpc} \) for a slope of \( 
\gamma = 1.6 \), which should be considered an upper limit for the much fainter galaxies we consider, which are likely to cluster less strongly. If we use the Adelberger & Steidel (2005) correlation function to calculate the factor of \( \chi_{\perp} \) in Equation (13), then we find that the size of the absorber galaxies has to be

\[
r_{\text{gal}} = 91 \text{ kpc} \left( \frac{C}{0.35} \right)^{1/2} \frac{n_{\text{LBG}}}{6.9 \times 10^{-3} \text{ cm}^{-3}}^{-1/2} \times \left( \frac{1 + \chi_{\perp}}{9} \right)^{-1/2}. \tag{24}
\]

Since this value for \( r_{\text{gal}} \) is very similar to \( R_{\perp} \), there is little point in distinguishing between the star-forming galaxy halo and the quasar halo, or stated in a different way, the average number of LBGs in the cylindrical volume set by \( R_{\perp} \) and \( \Delta D \) is, including the effects of clustering, about one \( (n_{\text{LBG}} = 0.8) \). Thus, associating the high-metallicity absorbing clouds with faint LBGs does not help explain the high covering factor of enriched material at large impact parameter.

If the absorption is to be associated with galaxies near the quasar, they must arise from a population much more abundant than \( L \sim 0.1 L_\odot \) galaxies. These dwarf systems will be significantly fainter and smaller. If we arbitrarily choose a value of \( r_{\text{abs}} = 20 \text{ kpc} \) for their absorption cross-section radius, then Equation (13) implies a comoving number density of \( n_{\text{dwarf}} = 0.14 \text{ Mpc}^{-3} \). Hence, if galaxies clustered around the quasar have \( r_{\text{abs}} = 20 \text{ kpc} \) then they must be 20 times more abundant than the faintest photometric LBGs studied to date. Extrapolating the Reddy et al. (2008) luminosity function fit to achieve this number density implies \( L \sim 10^{-3} L_\odot \), or an apparent magnitude limit of \( R < 31.7 \). The challenge to this scenario, however, is achieving a nearly solar metallicity in these extremely faint, high-\( z \) dwarf galaxies. Indeed, the DLAs are thought to arise from a population of faint galaxies and are likely to have an absorption size \( r_{\text{abs}} \) comparable to what we assume, but their metallicities are much lower (see Figure 7) and similarly low metallicities are seen locally in dwarf galaxies.

5.4. Are the Kinematics Tracing an Outflow?

How do we explain the presence of such a large gas mass of highly enriched material with a broad-line-region-like enrichment pattern at such a large distance from the quasar \( (r \sim 100 \text{ kpc}) \)? It is tempting to associate the absorbing material with a large-scale outflow or galactic wind from SDSSJ1204+0221FG and/or its host galaxy. Indeed, quasars exhibit fast outflows in the form of BAL systems on small scales (within 100 pc of the engine) and on large scales as radio jets extending to tens of kpc. Furthermore, high-\( z \) quasars are believed to reside in actively star-forming galaxies perhaps with
highly elevated star formation rates. Such galaxies may drive fast outflows that, in principal, could extend to tens or even hundreds of kpc.

Therefore, in terms of an outflow, there are two extreme scenarios to consider: (1) a highly collimated outflow such as a radio jet associated with the quasar and (2) a large-scale, expanding “bubble” of cold swept up material driven by star formation feedback and/or the quasar accretion power. The first “jet” scenario naturally yields an asymmetric velocity field relative to the host galaxy’s velocity vector. The required asymmetric outflow has been suggested as a viable model for reproducing the high incidence of optically luminous star-forming galaxies (e.g., Pettini et al. 2001; Martin 2005). Finally, theoretical treatments of outflows generally observed in star-forming galaxies (Pettini et al. 2001; Martin 2005). In what follows we will use the observed properties of SLLS/SDSSJ1204+0221BG to estimate, in an order of magnitude sense, the energetics of the presumed outflow, under the assumption that we have detected cold swept up material. We then consider if an outflow with these energetics could be plausibly produced by a starburst or AGN.

The mass of a shell of material at radius r_p, with column density N_p, and covering solid angle Ω_p, is M_p = m_p N_p Ω_p r_p^2. If this shell is outflowing at velocity v_p in a wind, the mass outflow rate is M_p ∼ M_e v_p/r_p. For our fiducial values and Ω_p = 2π, we derive M_p ∼ 3 × 10^{11} M⊙ and M_p ∼ 3000 M⊙ yr^{-1}. Note that we have taken the outflow velocity to be v_p = 1000 km s^{-1} because SLLS/SDSSJ1204+0221BG shows velocity separations as large as ∼ 700 km s^{-1} from the f/g quasar, but this represents only the radial component of the velocity vector. The corresponding energy, power, and momentum deposition rate of the wind are E_w ∼ 1/2 M_e v_p^2, E_w ∼ 1/2 M_e v_p^2, and P_w ∼ 1/2 M_e v_p^2, respectively. With our fiducial values, these are E_w ∼ 3 × 10^{46} erg, E_w ∼ 9 × 10^{44} erg s^{-1}, and P_w ∼ 2 × 10^{33} erg cm s^{-2}.

These crude estimates can be compared with the momentum and energy-driven winds of a starburst and/or AGN. Following the formalism presented in Murray et al. (2005), the SN deposition rate for a starburst galaxy with star formation rate M_e is P_{SN} ∼ 2 × 10^{33} M_e/(M⊙ yr^{-1}) g cm s^{-2}. A similar deposition rate is inferred from radiation pressure from assuming the gas is optically thick to absorption by dust grains. We conclude that if the absorption in SLLS/SDSSJ1204+0221BG is from material swept up in a large-scale wind, the star formation rate required to power the momentum flow is extremely large M_e ∼ 10^4 M⊙ yr^{-1}. Furthermore, this estimate should be considered a lower limit because it assumes all momenta deposited into the galaxy are assumed to add coherently which can significantly overestimate the deposition (Socrates et al. 2008).

The rest-frame near-UV luminosity from such a high star formation rate can be estimated (Kennicutt 1998), and it is L_UV ∼ 10^{47} erg s^{-1}; this would outshine the quasar bolometric luminosity L_QSO ∼ 1.4 × 10^{46} erg s^{-1} by an order of magnitude, which can easily be ruled out since a starburst spectrum is not observed in SDSSJ1204+0221FG or detected in the SDSS imaging. While the starburst could be significantly extinguished by dust (this is in fact an implicit assumption), the fact that we observe the f/g quasar unextinguished along our line of sight implies that we should have been able to see some evidence for a starburst 10 times brighter. Finally, we note that radiation pressure from the quasar radiation is also unable to drive the presumed outflow,17 since P_{QSO} = L_QSO/c ∼ 5 × 10^{37} erg cm s^{-2}, which is a factor of 40 lower than our estimate.

Next, we consider the wind power, again following the formalism in Murray et al. (2005). For SNe, assuming a rate of one per 100 yr per 1 M⊙ yr^{-1}, the SNe energy can only power the outflow for an extremely large star formation rate: M_e ∼ 3 × 10^4 M⊙ yr^{-1}. We conclude that the kinematics of SLLS/SDSSJ1204+0221BG are not driven by SN winds and consider, instead, the energy from the AGN. The absolute B-band magnitude of SDSSJ1204+0221FG is M_B = −24.8, which corresponds to a bolometric luminosity of L_QSO = 1.4 × 10^{46} erg s^{-1}, where we used the McLure & Dunlop (2004) fit to the Elvis et al. (1994) bolometric correction to determine L_QSO from M_B. The ratio of the outflow power to the accretion power is then

\[ E_w/L_QSO \sim 0.06 \left( \frac{\Omega_p}{2\pi} \right) \left( \frac{N_p}{10^{20.6} \text{ cm}^{-2}} \right) \left( \frac{R_{\perp}}{108 \text{ kpc}} \right) \times \left( \frac{v_p}{1000 \text{ km s}^{-1}} \right)^3 \text{ erg.} \]  

(25)

If indeed the AGN is powering an outflow, then ∼ 6% of the accretion power has been coupled to the host via a large-scale wind. A similar comparison can be made between the energy of the outflow, which is E_w ∼ 4 × 10^{46} erg and the rest-mass energy liberated to grow the supermassive black hole E_{BH} = \epsilon_{rad} M_{BH} c^2. Assuming an Eddington ratio of f_{edd} = L_{QSO}/L_{edd} = 0.1, consistent with recent estimates for a quasar at z ∼ 2.5 near the luminosity of SDSSJ1204+0221FG (Kollmeier et al. 2006; Shen et al. 2008a), we deduce a black hole mass of M_{BH} = 1.1 \times 10^9 (\frac{f_{edd}}{0.1})^{-1} M⊙. Thus, we can write

\[ E_w/E_{BH} \sim 0.01 \left( \frac{f_{edd}}{0.1} \right) \left( \frac{f_{edd}}{0.1} \right)^{-1}. \]  

(26)

17 Here, we are imagining that the quasar, viewed from another direction, emits a similar bolometric luminosity but is obscured by dust grains which absorb momentum.

18 We compute the cross-filter K-correction K_B(i), between apparent magnitude i and absolute magnitude B, which allows us to determine M_B from the SDSS i-band photometry.
To summarize, if the $H_\mathrm{i}$ and metal-line absorption in SLLS/SDSSJ1204+0221BG are from material swept up in a large-scale outflow, then the energetics are extreme. Starburst feedback is highly unlikely unless we are willing to consider unprecedented star formation rates $M_\star \gtrsim 10^4 M_\odot \, \text{yr}^{-1}$. Radiation pressure feedback from the quasar cannot drive the outflow even if all of the bolometric luminosity was absorbed by dust grains. Although large, the implied power of the presumed outflow is only a few percent of the bolometric luminosity of the f/g quasar, or similarly, its energy is of the order a percent of the radiated rest-mass energy required to grow an $\sim 10^6 M_\odot$ black hole. It is intriguing that we are led to deduce a few percent coupling between the black hole accretion and the host galaxy. This is very similar to the coupling factors used in simulations of quasar feedback. For instance, Springel et al. (2005a) must inject a fraction $\eta = 0.05$ of the accreted energy into the host galaxy to reproduce the observed $M_{\text{bol}} - \sigma$ correlation, where $\eta$ is defined by $E_{\text{feedback}} = \eta E_{\text{acc}} M_{\text{BH}} c^2$ (see also Grarto et al. 2004). However, if such a large amount of energy is being deposited in the host galaxy, radiative losses from the wind could be significant, which we have not considered. Thus, in effect, our estimate of the coupling factor is a lower limit.

Finally, it is worth noting that high speed outflows of cold gas have been identified in a small sample of post-starburst galaxies at $z \sim 0.5$ (Tremonti et al. 2007). In several cases the wind speeds exceed $1000 \, \text{km} \, \text{s}^{-1}$ and the authors also argue that the energetics may require prior quasar activity. Similarly, the high speeds of NAALs detected in quasars are also suggestive of fast outflows (D’Odorico et al. 2004; Wild et al. 2008). However, the mass and energetics of these outflows, detected along the line of sight to background sources, cannot be reliably estimated because of the highly uncertain column density of the absorbers and the unknown distance to the absorbing gas.

6. SUMMARY

In this paper, we introduced a novel technique to study the physical state of gas in the halos of luminous quasars, which has the potential to provide powerful constraints on the physical processes governing the formation of massive galaxies. By mining the sky for very rare close associations of quasars (Hennawi 2004; Hennawi et al. 2006a, 2006b), we previously discovered SDSSJ1204+0221, a close projected quasar pair with angular separation $\theta = 13.3 \, \text{arcsec}$ corresponding to $R_\perp = 108 \, \text{kpc}$ at the redshift of the foreground quasar $z_{\text{fg}} = 2.4360 \pm 0.0005$, precisely determined from Gemini/GNIRS spectroscopy. The spectral and photometric properties of SDSSJ1204+0221FG make it an unremarkable quasar at $z \sim 2.4$. It has an SDSS i-band magnitude of $i = 20.5$, from which we estimate a bolometric luminosity of $L_{\text{bol}} \sim 1 \times 10^{46} \, \text{erg} \, \text{s}^{-1}$, corresponding to a supermassive black hole mass $M_{\text{BH}} \sim 1.1 \times 10^9 M_\odot$, if the black hole accretes at one-tenth of the Eddington limit. The luminosity of SDSSJ1204+0221FG places it near the “knee” of the $z \sim 2.5$ quasar luminosity function (Croom et al. 2004; Richards et al. 2006), and the clustering of such quasars indicates they inhabit massive dark halos $M \sim 10^{13.3} M_\odot$ (Croom et al. 2001; Porciani et al. 2004; Croom et al. 2005), making them the progenitors of massive red and dead galaxies observed today. Our impact parameter $R_\perp$ easily resolves the expected virial radius $r_{\text{vir}} = 250 \, \text{kpc} (M/10^{13.3} M_\odot)^{1/3}$, and pierces the halo of SDSSJ1204+0221FG at about the cooling radius, where gas shock-heated to the virial temperature should take about a Hubble time to cool.

Rather, the only remarkable thing about SDSSJ1204+0221FG is that it forms a close projection with a b/g quasar ($z_{\text{bg}} = 2.53$) which is bright enough ($r = 19.0$) for high-resolution spectroscopy. Our Keck HIRES of SDSSJ1204+0221BG, the first ever to probe the halo gas of a f/g quasar, resolves the velocity fields of the absorbing gas and allows us to measure precise column densities for $H_\mathrm{i}$ and the ionic transitions of metals like Si, C, N, O, and Fe. These measurements allow us to place constraints on the physical state of the gas near the f/g quasar, such as its kinematics, temperature, ionization structure, chemical enrichment patterns, volume density, the size of the absorbers, the intensity of the impenetrable radiation field, as well as test for the presence of hot collisionally ionized gas. We first summarize the results for our single sightline, and then discuss their implications for massive galaxy formation and the quasar phenomenon.

6.1. Model-Independent Constraints

In our Keck/HIRES of SDSSJ1204+0221BG, we identify an SLLS with a redshift $z = 2.44$. A Voigt-profile fit to the Ly$\alpha$ and Ly$\beta$ profiles implies a total $H_\mathrm{i}$ column density $N_{H_\mathrm{i}} = 10^{19.65+0.15} \, \text{cm}^{-2}$. The $H_\mathrm{i}$ absorption occurs redward of $z_{\text{fg}}$, spanning from $\delta v = +50$ to $+780 \, \text{km} \, \text{s}^{-1}$. There is no $H_\alpha$ absorption detected ($N_{H_\alpha} \lesssim 10^{13.5} \, \text{cm}^{-2}$) in the velocity interval $\delta v = -1500$ to $0 \, \text{km} \, \text{s}^{-1}$. We identify a series of metal lines coincident in velocity with the $H_\alpha$ absorption (distributed in three primary components) that includes transitions from a range of ionization states of C, O, Fe, Si, Al, and N. We observe an integrated $O^+/H^0$ ratio of $[N(O^+)/N(H^0)] = -3.9 \, \text{dex}$ which indicates a highly enriched gas. Ignoring IC to this ratio, which should be negligible, the average gas metallicity is $[O/H] = -0.5 \, \text{dex}$. Both the extreme kinematics and high metallicity of this system are highly uncommon for intervening SLLSs.

The Doppler parameters of the low and intermediate ions are small ($b \lesssim 5 \, \text{km} \, \text{s}^{-1}$) indicating a gas temperature $T \sim 20,000 \, \text{K}$. At all velocities we observe an ionic ratio $N^{\text{O}^+}/N^{\text{N}^+} > 1$ which implies the gas is predominantly ionized. We observe weak, if any) C IV, N v, and O vi absorption indicating a modest (or negligible) quantity of metal-enriched gas with $T \sim 10^5$ to $10^6 \, \text{K}$ in the halo surrounding SDSSJ1204+0221FG.

6.2. Model-Dependent Constraints

Under the assumption that the gas is photoionized by a hard radiation field (e.g., the nearby quasar or the EUVB), we estimate an ionization parameter $log U = -3.0 \pm 0.3$ for the gas. This implies an ionization fraction $x = 0.96$ for the two lower column density components, and $x = 0.2$ for the component with the largest column. The total implied hydrogen column density of the system is $N_H = 10^{20.6} \, \text{cm}^{-2}$. Applying IC to the observed $N^{\text{O}^+}/N^{\text{O}^0}$ ratio, we infer solar to super-solar N/O abundances. At high $z$, such large N/O values are only found in gas associated with quasar environments. At $\delta v \approx +700 \, \text{km} \, \text{s}^{-1}$, we detect absorption from the excited fine-structure level of C IV, C iv* 1335. Under the assumptions that electron collisions dominate the C IV excitation and that $N(C^+) = N(Si^+) + \log(C/Si)_\odot$, we estimate an electron density $n_e = 0.2 \, \text{to} \, 10 \, \text{cm}^{-3}$. Comparing this volume density to the ionization corrected column density, we determine characteristic sizes $\ell \sim 10$ to $100 \, \text{pc}$ for the absorbing “clouds.”

The properties of the SLLS toward SDSSJ1204+0221BG—$z \approx z_{\text{fg}}$—extreme kinematics, high metallicity, and a solar N/O ratio—argue that this gas is located within the halo.
of SDSSJ1204+0221FG. There is an additional statistical argument: the strong clustering of optically thick absorbers around $z \sim 2$ quasars (Hennawi & Prochaska 2007) implies the SLLS is likely to lie at a distance near the observed transverse distance (see Figure 6). We summarize in the next subsection several interpretations drawn from associating SLLS/SDSSJ1210+0221FG with the galactic halo of SDSSJ1204+0211FG.

We tested the hypothesis that the SLLS/SDSSJ1204+0221BG is illuminated by ionizing radiation from f/g quasar by comparing the radiation field intensity inferred from the analysis of the SLLS against the value expected from SDSSJ1204+0221FG. Adopting the most conservative parameters for the SLLS ($\log U = -3$ and $n_H = 5 \text{ cm}^{-3}$), illumination of the SLLS cannot be ruled out if it is located at $r = R_\perp = 108$ kpc from SDSSJ1204+0221FG. Adopting more realistic values ($\log U = -4$ and $n_H = 1 \text{ cm}^{-3}$), we conclude that SLLS/SDSSJ1204+0221BG is not illuminated by SDSSJ1204+0221FG, unless the SLLS is located at an unlikely distance of greater than 500 kpc. We further demonstrated that if a system like SLLS/SDSSJ1204+0221BG were located along the sightline to a bright quasar at $r < 100$ kpc, and hence illuminated, then it would exhibit properties characteristic of the NAAL systems. This would include strong absorption by high ion transitions of O vi, N v, and C iv, optically thin H i absorption, and solar chemical abundances. The absence of strong high-ion absorption in this SLLS further suggests it is not illuminated by SDSSJ1204+0221FG and it also indicates that there is not a large reservoir of warm ($T \approx 10^4$ to $10^5$ K) gas in the halo surrounding the quasar. We suggest that there may still be a diffuse shock-heated medium but that it has a high temperature ($T > 10^4$ K), characteristic of the virial temperature of the massive dark matter halo $M \gtrsim 10^{13} M_\odot$ expected to be hosting the f/g quasar. If it exists, this material remains undetectable in absorption with the transitions accessible with our b/g quasar spectrum.

6.3. Interpretation and Outlook

The covering factor of cold $T \sim 10^4$ K, neutral, optically thick gas is nearly unity for transverse sightlines to $z \sim 2$ quasars with $R_\perp \lesssim 100$ kpc (Hennawi et al. 2006a), although this high column density absorbing gas is rarely observed along the line of sight to individual quasars (Russell et al. 2006; Prochaska et al. 2008b). The explanation for this anisotropic absorption is that the transverse direction is much less likely to be illuminated by the f/g quasar ionizing flux, because of either obscuration or intermittent emission (Hennawi et al. 2006a; Hennawi & Prochaska 2007; Prochaska et al. 2008b). Besides this anisotropic absorption pattern, several independent lines of evidence corroborate this picture for the case of SDSSJ1204+0221. First, we modeled the ionization state of SLLS/SDSSJ1204+0221BG which indicates that the gas is unlikely illuminated by SDSSJ1204+0221FG (see Section 4.4). Second, we failed to detect high ion transitions like N v or O vi that should have been seen if the gas were highly ionized by a hard radiation field (see Section 4.3). Third, we showed that if gas clouds similar to those in SLLS/SDSSJ1210+0221BG were at a similar distance along the line of sight (and hence illuminated), they would explain the population of much more highly ionized associated NAALs, commonly detected in quasar spectra (see Section 4.5). Fourth, fluorescent Ly$\alpha$ emission is not observed near $R_\perp$ in SDSSJ1210+0221 (J. F. Hennawi & J. X. Prochaska 2009, in preparation), whereas the clouds responsible for the high covering factor of optically thick gas (Hennawi et al. 2006a) near quasars (three such clouds were detected in SLLS/SDSSJ1204+0221BG) would be emitting detectable Ly$\alpha$ photons if illuminated (J. F. Hennawi & J. X. Prochaska 2009, in preparation). The upshot of this anisotropic illumination picture is that the b/g quasar sightline probes the physical state of gas near SDSSJ1204+0221FG which is shadowed and hence unaltered by the intense ionizing radiation emitted by the f/g quasar.

By combining the statistical covering factor measured by Hennawi & Prochaska (2007) with the total $N_H$ column determined for SLLS/SDSSJ1204+0221BG, we argued in Section 5.2 that the amount of cold gas at $r \sim 100$ kpc is significant, amounting to $\sim 3 \% (0.3 \pm 0.1) \Omega_m$ of the total expected gas density of the f/g quasar’s dark matter halo, if the gas fraction $f_g$ is equal to the cosmic baryon fraction $\frac{c_m}{\Omega_m}$. Similarly, if one assumes the material is distributed in a thin shell of radius $R_\perp$ which subtends $\Omega = 2\pi$, the implied gas mass is $M \sim 3 \times 10^7 M_\odot$. Although we have deduced much about the physical state of this cold gas (see Table 4), its origin is still unclear. The biggest clue could lie in its extreme enrichment patterns. The nearly solar metallicity of SLLS/SDSSJ1204+0221BG and its roughly solar N/O relative abundance make it anomalous relative to the population of intervening SLLS and DLAs (see Figure 7). Indeed, at $z \sim 2.5$ such high metallicities have only been observed on kpc scales in starburst galaxies (Pettini et al. 2001; Steidel et al. 2003) and solar N/O has only been observed in the broad-line regions of quasars (Dietrich et al. 2003; Arav et al. 2007) or in the NAALs (D’Odorico et al. 2004).

How do we explain the presence of such a large cold gas mass of highly enriched material with a broad-line-region–like enrichment pattern at such a large distance from the quasar $r \sim 100$ kpc? It is tempting (and fashionable) to associate the absorbing material with a large-scale outflow or galactic wind. If we are observing dense material swept up by an outflow, then the energetics are extreme $E_w \sim 10^{45}$ erg s$^{-1}$. A starburst cannot drive this wind unless we are willing to consider unprecedented star formation rates $\dot{M}_*$ $\gtrsim 10^4 M_\odot$ yr$^{-1}$. Radiation pressure feedback from the quasar cannot drive an outflow with this power even if its bolometric luminosity were completely absorbed by dust grains (along a different direction than our line of sight). However, the power of the flow is only a few percent of SDSSJ1204+0221BG’s estimated bolometric luminosity, or similarly, its energy is of the order of a percent of the radiated rest-mass energy required to grow a $\sim 10^9 M_\odot$ black hole. So, the feedback hypothesis suggests a coupling between black hole accretion and outflow which is comparable to the value used by simulators to reproduce the supermassive black hole $M_{BH} – \sigma$ correlation (e.g., Springel et al. 2005a). Furthermore, radiative losses from such an energetic flow could be significant, so our estimate of the coupling factor must be considered a lower limit. If we are in fact observing feedback in SLLS/SDSSJ1204+0221BG, then the kinematics, radial extent, and high metallicity of the emergent outflow bear intriguing similarities to the giant Ly$\alpha$ nebulae observed in HzRGs. However, it is difficult to explain why such an energetic outflow would result in so little material at intermediate temperature $T \sim 10^4$–$10^5$ K, which we would have easily detected (but did not; see Section 4.3).

But, we may not be observing an outflow at all. The observed kinematics in SLLS/SDSSJ1204+0221BG, although extreme relative to the intervening SLLS population, are consistent with the expected gravitational motions if the f/g quasar is
indeed hosted by a massive dark matter halo $M \gtrsim 10^{13}M_\odot$, as indicated by the strong clustering of $z \sim 2.5$ quasars (Croom et al. 2001; Porciani et al. 2004; Croom et al. 2005). In this alternative scenario, the absorption is being caused by cold clouds, with sizes $r_{abs} = 10–100$ pc, unit covering factor and implied volume filling factor $C_v \sim 10^{-5} – 10^{-4}$, which are either infalling or virialized in the deep potential well of the massive dark matter halo. We estimated the pressure of these clouds to be $P \sim 10^9Kcm^{-3}$, which intriguingly matches the pressure of the $T_{vir} \sim 10^7$ K shock-heated gas expected to permeate the massive dark matter halo hosting the $f/g$ quasar. This pressure equilibrium is reminiscent of a large class of galaxy formation models that postulate cold $T \sim 10^4$ K clouds pressure confined by a hot shock-heated virialized medium (Mo & Miralda-Escude 1996; Maller & Bullock 2004; Dekel & Birnboim 2006), and these scenarios might explain the lack of significant intermediate temperature $T \sim 10^{-6}$ K gas near the $f/g$ quasar. However, if we are indeed detecting pressure-confined cold clouds undergoing gravitational motions, why should these clouds have such a high metallicity? This question is all the more puzzling considering that the expected cooling time of the tenuous virialized hot gas would be comparable to the Hubble time at $r \sim 100$ kpc. While it may be more plausible to associate the cold gas and metals with star-forming galaxies clustered around the quasar, they would need to be extremely abundant $n \sim 0.1$ Mpc$^{-3}$ to produce the near unit covering factor of cold gas and metals. These faint $L \sim 10^{-3}L_\odot$ dwarf galaxies would need to enrich spheres of $r_{abs} \sim 20$ kpc to solar metallicity, which seems implausible in light of the low metallicities observed in most DLAs (see Figure 7) and the similarly low values seen locally in dwarf galaxies.

With just a single sightline, we cannot distinguish between a quasar-powered outflow or cold clouds undergoing gravitational motions. However, similar observations of a statistical sample of projected quasar pairs stand to teach us a tremendous amount about the physics of massive galaxy formation. This is nicely illustrated by the preliminary comparison of the absorption-line properties of $z \sim 2.2$ quasars to $z \sim 2.3$ star-forming galaxies presented in Figure 11. The primary motivation for this comparison is that, across the two populations, we are afforded a mass baseline of more than an order of magnitude. The clustering of star-forming galaxies at $z \sim 2$ indicates that they inhabit dark matter halos with $M \lesssim 10^{12}M_\odot$, making them the likely progenitors of $L_\star$ galaxies that inhabit the “blue-cloud” of the color–magnitude diagram today (Conroy et al. 2008); whereas, the stronger clustering of quasars at $z \lesssim 2$ implies larger halo masses $M \gtrsim 10^{13}M_\odot$ (Croom et al. 2001; Porciani et al. 2004; Croom et al. 2005), making them progenitors of massive red-and-dead galaxies on the red sequence. Hence, in comparing quasars to star-forming galaxies at $z \sim 2$, we are effectively comparing the progenitors of quenched galaxies to those of unquenched galaxies.

The lower panel of Figure 11 plots the H I column density of absorbers at the $f/g$ quasar (or galaxy) redshift versus the impact parameter to the $b/g$ quasar sightline. The (red) circles are the 13 $f/g$ quasars ($\Delta z = 2.2$) with a background quasar within $R_\perp < 350$ kpc uncovered by Hennawi et al. (2006a), and (blue) squares are seven $f/g$ star-forming galaxies ($\Delta z = 2.3$) studied in absorption against a bright $b/g$ quasar by Simcoe et al. (2006). The vertical rectangles in the upper panel illustrate the range of metallicities encountered in the individual components of each system at each impact parameter. The only $f/g$ quasar metallicity measured thus far is for SDSSJ1204+0221 (this work), whereas Simcoe et al. (2006) measured metallicities near six $f/g$ galaxies.

Two notable features of Figure 11 warrant further discussion. First, at $R_\perp \approx 100$ kpc, one galaxy and one quasar metallicity have been measured, and both indicate abundances near solar. Simcoe et al. (2006) attributed the high metallicity of their smallest impact parameter system (MD103) to galaxy formation feedback, and we similarly cited the high metallicity of SDSSJ1204+0221 as the most compelling argument for an outflow powered by the quasar. By mapping out the run of abundance–impact parameter in this plot, one could characterize the size of the enriched regions around protogalaxies with a significant mass lever arm. If feedback is responsible for the metals at large impact parameters, measuring the abundance–impact parameter relation would constrain the energetics and transport processes characterizing the relevant feedback mechanism. Furthermore, this measurement would be fundamental to any discussion of the enrichment history of the IGM and the ICM.

The second noteworthy feature of Figure 11 is that on small scales the $f/g$ quasars appear to have $N_{HI}$ column densities significantly larger than the $f/g$ galaxies. This comparison is complicated by the fact that the dark matter halos that host the quasars are expected to be larger and more massive than those hosting the galaxies. For reference, Conroy et al. (2008) estimated that the average halo mass of $z \sim 2$ star-forming galaxies to be $M = 10^{12}M_\odot$, which implies a virial radius $r_{vir} = 89$ kpc; whereas, at $z \sim 2.4$ we are using $M = 10^{13.3}M_\odot$ implying $r_{vir} = 250$ kpc (Porciani et al. 2004). At an impact
parameter of $R_\perp = 100$ kpc, the ratio of the total hydrogen column densities of these dark matter halos is $n_{\text{H}_2}^{\text{QSO}}/n_{\text{H}_2}^{\text{gal}} = 5$, whereas the quasars in Figure 11 have H I column densities a factor of $\gtrsim 100$ times larger than the galaxies for $R_\perp \lesssim 200$ kpc. Although we caution that the statistics in the lower panel of Figure 11 are still very poor, it is nevertheless interesting to speculate about the implications of this tentative result.

Why would the quasars have a much larger reservoir of cold gas at $R_\perp \sim 100$ kpc, of the order of a few percent of the total expected gas density (see Section 5.2), than star-forming galaxies? Can this difference be attributed to a distinct feedback mechanism operating in quasars that does not occur in star-forming galaxies? If instead the absorbers at $R_\perp \sim 100$ kpc arise from cold gas accretion rather than outflows, then the larger relative density of cold gas around quasars is particularly puzzling. Cosmological hydrodynamical simulations predict the opposite trend with dark halo mass: cold accretion accounts for a smaller fraction of the total accreted gas in higher mass halos where shocks become stable throughout the halo and the cold filamentary mode of accretion disappears (Kereš et al. 2005; Dekel & Birnboim 2006; Ocvirk et al. 2008). Whether the cold gas around quasars is ejected by feedback or accreted in gravitational collapse, what is the ultimate fate of this material? Does it eventually fall back onto the quasar host galaxy or do the gas and metals blend into the IGM? Do we expect to observe a similar cold halo of gas around nearby massive elliptical galaxies, since their progenitors are $z \sim 2$ quasars like SDSSJ1204+0221PG?

Although preliminary, the putative trends in Figure 11 provoke fundamental questions about feedback, quenching, and the physics of massive galaxy formation. Yet, this discussion represents just two measurements (metallicity and $N_{\text{HI}}$) gleaned from our analysis of the spectrum of SDSSJ1204+0221BG. Other properties of the gas such as its kinematics, temperature, ionization structure, relative abundance patterns, the presence or absence of a hot collisionally ionized phase, and the volume density and size of the clouds have a similar potential to constrain the physics of massive galaxy formation if they can be mapped out for statistical samples. Such a statistical analysis is well within reach. To date, our pair confirmation program (Hennawi 2004; Hennawi et al. 2006a, 2006b) has confirmed about 90 pairs of quasars with impact parameter $R < 300$ kpc and $z_{\text{fg}} > 1.6$, and about a comparable number still remain to be discovered in the existing SDSS photometric data. Of the known pairs, only about five are bright enough $r \lesssim 19$ for high-resolution (FWHM $\sim 10$ km s$^{-1}$) echelle spectroscopy like the HIRES used to study SLLS/SDSSJ1204+0221BG. However, higher throughput but lower resolution echelle spectrographs, such as the Echellette Spectrograph and Imager (ESI; Sheinis et al. 2002) on Keck II, the Magellan Echellette (MagE) on the Magellan Clay Telescope, or the planned X-Shooter spectrograph (D’Odorico et al. 2006) for the VLT, can deliver spectra with FWHM $\sim 30$–50 km s$^{-1}$ and the required S/N ($\sim 10$ per resolution element), in 1–2 hr for $r \lesssim 21.5$, which would make all of the quasar pairs known observable. Although these instruments have lower spectral resolution, they roughly resolve the H I Lyman series affording precise estimates of $N_{\text{HI}}$. Furthermore, such data would yield metallicity and relative abundance estimates to a precision of 0.3 dex, and would allow for the construction of photoionization models with an accuracy comparable to that achieved in this work.

The most important aspect of the approach taken to understanding galaxy formation in this study and (Simcoe et al. 2006; see also Adelberger et al. 2003) is that they provide the first observational constraints on the physical state of the gas on scales $\gtrsim$ kpc in high-z protogalaxies. Although the ideas behind quenching and feedback were introduced to explain the observed properties of local galaxy stellar populations, such as the bimodality in the color–magnitude diagram (Strateva et al. 2001; Baldry et al. 2004; Bell et al. 2004; Blanton et al. 2005; Faber et al. 2007), and the sharp cutoff in the luminosity function (Benson et al. 2003), these are fundamentally gas dynamics problems. Many of the relevant hydrodynamical and physical processes can be (or are nearly) resolved by simulation grids with current technology. Conversely, predicting how this gas physics manifest itself in the stellar populations of local or high-z galaxies requires that the uncertain “subgrid” physics of star formation be inserted by hand, or with the aid of semianalytical recipes. Thus, observational constraints on the gas provide especially fruitful comparisons to theory. If the techniques presented here for a single object can be expanded to statistical samples, that will constitute a significant step on the road toward understanding massive galaxy formation.

We acknowledge helpful discussions with T. J. Cox, P. Hopkins, P. Madau, B. Mathews, E. Ramirez-Ruiz, R. Simcoe, and A. Wolfe. We are grateful to R. Simcoe for kindly providing the galaxy data in Figure 11 in electronic form. For part of this work J.F.H was supported by NASA through Hubble Fellowship grant 01172.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555. JXP acknowledges funding through an NSF CAREER grant (AST-0548180) and NSF grant (AST-0709235). J.F.H is currently supported by the National Science Foundation through the Astronomy and Astrophysics Postdoctoral Fellowship program (AST-0702879).

The conclusions of this work are partly based on observations obtained at the Gemini Observatory through Gemini Program ID GS-2006A-Q-3. Gemini Observatory is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

The conclusions of this work are based on data collected from observatories at the summit of Mauna Kea. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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