A $\sim 6$ Mpc overdensity at $z \approx 2.7$ detected along a pair of quasar sight lines: filament or protocluster?*

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ABSTRACT

Simulations predict that gas in the intergalactic medium (IGM) is distributed in filamentary structures that connect dense galaxy clusters and form the cosmic web. These structures of predominantly ionized hydrogen are difficult to observe directly due to their lack of emitting regions. We serendipitously detected an overdensity of log N(H I) > 18.0 absorbers at $z = 2.69$ along the lines of sight toward a pair of background quasars. Three main absorption regions spanning $\sim 2000$ km s$^{-1}$ (corresponding to $6.4$ h$^{-1}$ Mpc proper) are coincident in the two lines of sight, which are separated by $\sim 90$ h$^{-1}$ kpc transverse proper distance. Two regions have [Fe/H] < $-1.9$ and correspond to mild overdensities in the IGM gas. The third region is a sub-DLA with [Fe/H] = $-1.1$ that is probably associated with a galaxy. We discuss the possibility that the lines of sight probe along the length of a filament or intercept a galaxy protocluster.

Key words. quasars: absorption lines – intergalactic medium – large-scale structure of Universe – quasars: individual: SDSS J091338.30-010708.7 – quasars: individual: J091338.96-010704.6

1. Introduction

Filamentary structures that emerge both from the large-scale distribution of galaxies and in cosmological simulations are iconic for the cosmic web (Bond et al. 1996). Filaments and sheets outline vast, extremely underdense regions known as voids, before meeting at nodes that coincide with matter-rich galaxy clusters. Various techniques are used to identify structures in cosmological simulations and trace filaments (e.g., Bond et al. 2010, Murphy et al. 2011, Zousbje et al. 2011, Smith et al. 2012, Cautun et al. 2014), the longest of which span more than $100$ h$^{-1}$ Mpc. Segments connecting two clusters are relatively straight with typical lengths of $5 - 20$ h$^{-1}$ Mpc and radial profiles that fall off beyond $2$ h$^{-1}$ Mpc (Colberg et al. 2005, González & Padilla 2010, Aragón-Calvo et al. 2010).

At low redshift, filament finding techniques applied to the Sloan Digital Sky Survey (SDSS; York et al. 2000) galaxy distribution measure maximum lengths comparable to simulations: $60 - 110$ h$^{-1}$ Mpc (Pandey et al. 2011, Tempel et al. 2014). The majority of galaxies lie within $0.5$ h$^{-1}$ Mpc of the filament axis (Tempel et al. 2014). Another strategy is to look for evidence of filamentary structures that connect a particular galaxy cluster to the cosmic web. Observations of clusters at $z \sim 0.5$ reveal that they are embedded in filaments extending more than $14$ h$^{-1}$ Mpc (Junaka et al. 2007, Verdugo et al. 2012). Complimentary to using galaxies as tracers, filaments can also be directly detected from weak gravitational lensing signals (Mead et al. 2010, Jauzac et al. 2012) unambiguously identify a filament with projected length $\sim 3.3$ h$^{-1}$ Mpc (3D length $13.3$ h$^{-1}$ Mpc) feeding into a massive galaxy cluster at $z = 0.55$.

At high redshift, diffuse H I in the intergalactic medium (IGM) imprints absorptions in the spectra of background quasars and creates the Lyman-alpha (Ly$\alpha$) forest. Correlations on scales $< 5$ h$^{-1}$ Mpc comoving in the Ly$\alpha$ forests of quasar lines of sight (LOS) with small angular separations (e.g., D’Odorico et al. 1998, Rolinde et al. 2003, Coppi et al. 2006, D’Odorico et al. 2006, Saitta et al. 2008, Cappetta et al. 2010) likely arise from filaments. Reconstruction methods applied to simulated and observed IGM absorptions recover the topology of this low-density gas at $z \sim 2$ (Cucci et al. 2008, Ciesewski et al. 2014). However, little is known observationally about the topology of the IGM, and the actual H I gas distribution may be less filamentary than simulated structures (Rudie et al. 2012). Currently, the source density limits our ability to resolve cosmic web filaments. Lee et al. (2014) suggest that observing programs with existing $8 - 10$ m telescopes could achieve the source density necessary to obtain a resolution of $\sim 3 - 4$ h$^{-1}$ Mpc over cosmologically interesting volumes. However, the next generation of 30 m-class telescopes will best address the challenge of resolving filaments (Steidel et al. 2009, Maiolino et al. 2013, Evans et al. 2014).

It is clear from these studies that quasar LOS intersect structures in the cosmic web. While they most often pass through the filament width, certain LOS foreseeably probe along the length. Here we present H I absorptions indicative of the gaseous environment within a filament. We detect multiple, consecutive absorptions at $z \approx 2.69$ with log N(H I) (cm$^{-2}$) $> 18.0$ that span nearly $2000$ km s$^{-1}$ and are coincident in both LOS toward a pair of quasars separated by about $1''$. 

* Based on observations with X-shooter on the Very Large Telescope at the European Southern Observatory under program 089.A-0855.
We describe the quasar spectra in Section 2, including how the close LOS pair was identified, and analyze the absorptions in each LOS in Section 3. In Section 4, we discuss evidence for whether the LOS intercept a galaxy protocluster or probe along the length of a filament. We use a $\Lambda$CDM cosmology with $\Omega_m = 0.73$, $\Omega_{\Lambda} = 0.27$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Komatsu et al. 2011).

2. Data
The targeted quasars relevant to this work are SDSS J091338.30-010708.7 at $z \sim 2.75$ ($r = 20.49$) and J091338.96-010704.6 at $z \sim 2.92$ ($r = 20.38$). We refer to them as the foreground (FG) and background (BG) quasar accordingly. Their angular separation is $10.74''$, which corresponds to $87.8 \text{ h}^{-1} \text{kpc}$ proper distance ($0.32 \text{ h}^{-1} \text{Mpc}$ comoving) at $z = 2.69$. These quasars were identified in the publicly available data release 9 quasar catalog (DR9Q; Paris et al. 2012) from the SDSS-III BOSS (Dawson et al. 2013).

A corresponding system appears in Noterdaeme et al. (2012b). A background quasar was flagged in the BG LOS at the redshift of FG quasar, proper distance ($0.05 \text{ h}^{-1} \text{Mpc}$) at $z = 2.69$.

Table 2. H$\alpha$ column densities [$\log(\text{N/cm}^2)$] for components along the BG and FG quasar LOS. Velocities (km s$^{-1}$) are relative to the BG-C system redshift, $z = 2.6894$.

| Comp. | Name (km s$^{-1}$) | BG log N(H$\alpha$) | FG log N(H$\alpha$) |
|-------|-------------------|-------------------|-------------------|
| BG-A1 | -1681             | 19.90             |                   |
| FG-A1 | -1675             | –                 | 14.32             |
| BG-A2, FG-A2 | -1432     | 19.67             | 18.57             |
|       | -1176             | 14.82             | 14.66             |
|       | -893              | –                 | 15.30             |
| BG-B  | -834              | 18.41             |                   |
| FG-B  | -800              | –                 | 18.77             |
|       | -719              | 15.20             | 14.54             |
|       | -680              | –                 | 14.39             |
|       | -451              | 14.92             |                   |
|       | -444              | –                 | 14.50             |
|       | -351              | –                 | 14.15             |
|       | -190              | –                 | 14.75             |
|       | -78               | –                 | 15.90             |
| BG-C  | 0                 | 20.15             |                   |
|       | 26                | –                 | 15.75             |
|       | 294               | 16.22             | –                 |

Initial interest in the pair was due to a damped Ly$\alpha$ absorption (DLA) in the BG LOS at the redshift of FG quasar, which offers an opportunity to study the host galaxy environment in absorption (Finley et al. 2013, and in preparation). In the low-resolution BOSS spectrum, an additional DLA with $\log N(\text{H} \alpha) = 21.05$ at $z_{\text{abs}} = 2.680$ is flagged in the BG LOS (NoteRdaeme et al. 2012b). A corresponding system appears in the FG BOSS LOS, but the low column density excludes it from the catalog of $\log N(\text{H} \alpha) \geq 20$ absorbers. Motivated by the absorption systems, we pursued a higher resolution analysis of these LOS.

The quasars were observed in service mode in spring 2013 with X-shooter on the 8.2m Kueyen (UT2) telescope at the European Southern Observatory as part of a program (ESO 089.A-0855, PI. Finley) targeting non-binary quasar pairs with small angular separations. The X-shooter spectrograph has UBV, VIS, and NIR arms that allow simultaneous observations across the full wavelength range from 300 nm to 2.5 μm. The total exposure times were $2 \times 3000 \text{s}$ (1.67 h) for the FG quasar and $5 \times 3720 \text{s}$ (5.17 h) for the BG quasar.

The data were reduced with version 2.2.0 of the ESO X-shooter pipeline (Modigliani et al. 2010). The bias level for the nominal resolution (R ≈ 8800), since the seeing was smaller than the $0.9''$ slit width. The resolution in the UBV (1.0'' slit width) is likewise approximately R ≈ 6400.

3. Absorption Systems
We identify consecutive intervening H$\alpha$ absorptions spanning $\Delta v = 2000 \text{ km s}^{-1}$ at $z \geq 2.69$ that are coincident in both LOS toward the J0913-0107 non-binary quasar pair. A proper distance of $\sim 90 \text{ h}^{-1} \text{kpc}$ at this redshift separates the FG and BG quasar LOS. Three main absorption regions are denoted A, B, and C in the two spectra (Figure 1). We fit the entire absorption structure with the VPFIT package to obtain system redshifts and column densities for the components (Figure 2). Seven absorptions have $\log N(\text{H} \alpha) (\text{cm}^{-2}) > 18.0$, and we refer to them by the LOS, absorption region, and component number: BG-A1, BG-A2, BG-B, BG-C, FG-A1, FG-A2, and FG-B. We discuss the absorption systems in each LOS.

3.1. Background Quasar Line of Sight
3.1.1. H$\alpha$ Absorption Systems
The H$\alpha$ absorption profiles for the components in regions A, B, and C are constrained from fitting Ly$\alpha$ – Ly$\beta$ in the UBV spectrum (Figure 2, left). The redshifts for components BG-A1 ($z = 2.6688$), BG-A2 ($z = 2.6718$), and BG-C ($z = 2.6894$) are fixed based on the fits to their associated low-ionization metal transitions (Figure 3). The absorption in region C is a log $N(\text{H} \alpha) (\text{cm}^{-2}) > 18.0$, and we refer to them by the LOS, absorption region, and component number: BG-A1, BG-A2, BG-B, BG-C, FG-A1, FG-A2, and FG-B. We discuss the absorption systems in each LOS.

The flux in the vicinity of Ly$\alpha$ is almost completely absorbed, except for a small peak separating region A from regions

http://www.ast.cam.ac.uk/~rfc/vpfit.html
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Fig. 1. Portion of the Ly\( \alpha \) forest with significant, coincident H\( \text{I} \) absorptions along both LOS. The FG spectrum (black) is overplotted on the BG spectrum (gray). The main absorption regions are labelled A (purple), B (blue), and C (red).

Fig. 2. Fits to Ly\( \alpha \) (top), Ly\( \beta \) (middle), and Ly\( \gamma \) (bottom) H\( \text{I} \) absorptions in the BG (left) and FG (right) spectra. Dashed purple, blue, and red lines mark the \( \log N(\text{H}\text{I}) > 18.0 \) components in regions A, B, and C, while dash-dotted purple, blue, and red lines indicate the weaker components within the respective regions. Dash-dotted blue-gray lines signal low column density components between the three main regions that are also part of the absorption structure. Dotted gray lines in the BG-Ly\( \alpha \) panel indicate blended components from Si\( \text{II} \) \( \lambda \lambda 1190, 1193 \) absorptions associated with \( z \approx 2.75 \) DLA.

Fig. 3. Diagram of H\( \text{I} \) clouds distributed along the FG and BG quasar LOS. Circle sizes scale with the H\( \text{I} \) column density such that twice the area represents eight times as much \( N(\text{H}\text{I}) \) \( \left( \text{Area} = N(\text{H}\text{I})^{1/3} \right) \). Low column density clouds, for which no metallicity is measured, are dark blue, while brighter, greener colors indicate clouds with higher metallicities. Zero velocity is at \( z = 2.6894 \).
Table 1. Column Densities [log(N/cm²)] for components of the log N(H) = 20.2 cm⁻² sub-DLA detected in the BG quasar LOS. Velocities (km s⁻¹) are relative to the BG-C system redshift, z = 2.6894. The main components of both O i and C ii are saturated.

| z   | v  | O i | σ(O i) | Si ii | σ(Si ii) | C ii | σ(C ii) | Al ii | σ(Al ii) | Al iii | σ(Al iii) | Fe ii | σ(Fe ii) |
|-----|----|-----|--------|-------|---------|------|---------|-------|----------|--------|-----------|-------|---------|
| 2.687165 | -180 | 14.32 | 0.04 | 13.31 | 0.08 | 14.75 | 0.11 | 12.22 | 0.06 | 11.69 | 0.35 | 12.95 | 0.05 |
| 2.688148 | -100 | 15.09 | 0.02 | 14.17 | 0.02 | 14.92 | 0.03 | 12.90 | 0.03 | 11.93 | 0.29 | 13.73 | 0.01 |
| 2.688912 | -38 | 16.23 | 0.33 | 14.11 | 0.04 | 15.10 | 0.14 | 13.35 | 0.10 | 12.21 | 0.13 | 14.16 | 0.03 |
| 2.689329 | -4 | 17.59 | 0.44 | 14.72 | 0.07 | 14.61 | 0.66 | 12.95 | 0.06 | 12.09 | 0.17 | 13.74 | 0.03 |
| 2.689953 | 47 | 14.89 | 0.03 | 14.04 | 0.02 | 15.07 | 0.03 | 12.76 | 0.03 | 11.57 | 0.90 | 13.58 | 0.02 |
| 2.692830 | 280 | 14.16 | 0.03 | 13.44 | 0.06 | 14.19 | 0.02 | 12.23 | 0.05 | - | - | 13.06 | 0.04 |

B and C at ~950 km s⁻¹. Components BG-A1 and BG-A2 are both sub-DLAs, with log N(H) i = 19.9 ± 0.1 and 19.7 ± 0.3 respectively. Strong Si ii λ1190, 1193 absorptions from z ≃ 2.75 DLA blend with the H i absorptions and contribute to the extended zero-level flux. The components in region B are more apparent in the Lyβ profile, and when they are included the fit to Lyα recovers the small peak near ~950 km s⁻¹. The strong component labelled BG-B (Figure 2 left) is a log N(H) i = 18.4 ± 0.2 Lyman limit system (LLS). All eight H i absorptions fitted in the BG spectrum are listed with their velocity offsets relative to the BG-C component in Table 2.

3.1.2. Abundances

Table 3 gives abundances for the LLS and sub-DLA systems in the three regions. The abundances are calculated with respect to solar values [Lodders 2003] following the convention [X/H] = log(N(X)/N(H)) - log(N(X)/N(H)☉).

The BG-A1 and BG-A2 metal absorptions are single-component, and we detect O i, which is a good indicator of the metallicity. Charge transfer processes imply that O i and H i are tightly related [Field & Steigman 1971]. Since both the O i λ1302 and O i λ1303 transitions are detected for the BG-A1 component, the absorption line fit is well-constrained. The oxygen abundance is [O i] = -1.19 ± 0.34. The Si, Al, and Fe abundances are slightly lower with [X/H] ≤ -1.7, -2.1, and -1.9 respectively. The BG-A1 C ii λ1334 absorption is blended with Si ii λ1304 from the z = 2.75 DLA. We estimate the de-blended C abundance, [C/H] ≤ -1.83 ± 0.59, by fixing the DLA N(Si ii) from other transitions and imposing the same FWHM as for the other BG-A1 absorptions.

The O i λ1303 transition is blended for the BG-A2 component, but the absorptions are not-saturated. The oxygen abundance, [O i] = -1.56 ± 0.43, is again slightly higher than the Si, C, Al, and Fe abundance [X/H] ≤ -2.1. The BG-A2 C ii λ1334 absorption is redder than the DLA Si ii λ1304 absorption and unaffected by blending.

The [C/O] values, -0.64 ± 0.68 for BG-A1 and -0.54 ± 0.55 for BG-A2, follow the trend where, in low-metallicity systems, [C/O] increases as [O/H] decreases [Cooke et al. 2011].

Dutta et al. 2014.

No metal transitions corresponding to the H i absorptions in region B are detected (Figure 4) to a limit of log N(O i) ≤ 13.0 ± 0.1. To obtain this estimate, we use the average FWHM from the detected BG-A1 and BG-A2 O i components and limit the absorption strength according to the noise in the flux. The upper limit on the [O/H] abundance is -1.80 ± 0.25.

The abundances for the region C sub-DLA, [Si/H] = -0.71 ± 0.11, [Al/H] = -0.89 ± 0.08, and [Fe/H] = -1.13 ± 0.18, are somewhat higher than the average value for intervening DLAs at z = 2.69, (Z) = -1.24±0.12 [Rakel et al. 2012]. The enhanced [Si/Fe] value, 0.41±0.21, is typical of intervening DLAs at this redshift and is likely due to dust depletion (Prochaska & Wolfe 2002; Vladilo 2002). Absorptions BG-A1, BG-A2, and BG-B all have abundances approximately an order of magnitude lower than that of BG-C.

3.2. Foreground Quasar Line of Sight

3.2.1. H i Absorption Systems

H i absorptions in the FG quasar Lyα forest have a similar structure as the systems in the same redshift range in the FG quasar spectrum (Figure 1). Weaker components separate the main concentrations of H i in regions A, B, and C. We fit thirteen components to the Lyα – Lyβ transitions for this absorption structure (Figure 2 right). Their column densities are listed in Table 2 along with the velocity offset relative to the BG-C component redshift. Three components, FG-A1, FG-A2, and FG-B, are in the LLS range, with log N(H) i = 18.5, 18.6, and 18.8 respectively, all with σ(N(H) i) ≤ 0.2. The remaining ten components are all below log N(H) i = 16.0. The highest column density components, FG-A1, FG-A2, and FG-B, are aligned with strong absorptions in regions A and B of the FG quasar LOS (Figure 3). The FG-A1 component is between the BG-A1 and BG-A2 components, whereas the FG-A2 is exactly aligned with BG-A2 and FG-B is offset from BG-B by less than 35 km s⁻¹. In region C, three lower column density components with log N(H) i ≥ 14.8, 15.9, and 15.8 occur within 200 km s⁻¹ of the BG-C sub-DLA.

3.2.2. Abundances

Low-ionization metals are detected only for the FG-A2 H i component (Figure 5). The C ii, Si ii, Al ii, and Fe ii absorptions are fitted with two components, as required to follow the C ii profile. The absorptions are weak, however, and often difficult to distinguish from the noise. Upper limits on the abundances are [C/H] ≤ -0.70 ± 0.48, [Si/H] ≤ -0.48 ± 0.40, [Al/H] ≤ -0.50 ± 0.45, and [Fe/H] ≤ -1.08 ± 0.47. Since the FG-A2 H i column density is log N(H) i = 18.6, the gas is not predominantly neutral and ionization corrections are likely significant. Both C ii and Si ii can be associated with the ionized gas.

To obtain a reliable metallicity indicator, we estimate an upper limit of log N(O i) ≤ 13.5 ± 0.1 for the three LLS, FG-A1, FG-A2, and FG-B, using the same process as in Section 3.1.2. Their corresponding metallicity limits are [O/H] ≤ -1.7, -1.8, and -2.0.

4. Discussion and Conclusions

We studied coincident H i absorptions that occur in LOS toward the FG and BG quasars in the J0913-0107 pair. Samples of close quasar pairs have been employed to measure quasar clustering when the redshift differences are negligible (e.g. [Hennawi et al.]).
Fig. 4. Fits to metal absorption lines in the BG quasar spectrum. Dashed purple, blue, and red lines mark components in regions A, B, and C. Thin dashed red lines indicate the six individual low-ionization components associated with region C. C IV absorptions are not detected for the BG-A1 and BG-A2 components, and no metal absorption lines associated with the BG-B component are detected. Si II λ1304 absorptions appear directly to the right of the O I λ1302 absorptions in the uppermost panel. The BG-A1 C iv component is blended with the Si ii λλ1304 absorption from a \( z \approx 2.75 \) DLA (dotted gray lines), but the BG-A2 component is unaffected. Dotted gray lines in the C IV \( \lambda \lambda 1548, 1550 \) panels likewise indicate components from the Si II \( \lambda 1526 \) absorption associated with the same \( z \approx 2.75 \) DLA. Zero velocity is at \( z = 2.6894 \), and the 1-σ error on the flux is shown in magenta.

Fig. 5. Fits to metal absorption lines in the FG quasar spectrum. Dashed purple and blue lines mark the strong H i components in regions A and B. Weak low-ionization transitions (C ii, Si ii, Al ii, Fe ii) associated with FG-A2 are fitted with two components. No C iv is detected in region A to a limit of log \( N(C iv) \) < 13.2 ± 0.1. For FG-B, only C iv is detected. Zero velocity is at \( z = 2.6894 \), and the 1-σ error on the flux is shown in magenta.

In this work, the velocity separation, metallicities, and kinematics for coincident H i absorptions along the studied region in the two J0913-0107 quasar spectra suggest that their LOS probe the same extended gaseous structure. Examining Figure 4 we notice that the absorption system kinematics and metallicities remain similar across the ~90 \( h_{70}^{-1} \) kpc proper (0.32 \( h_{70}^{-1} \) Mpc comoving) distance separating the two LOS. The highest column density absorptions in the FG LOS all have log \( N(Hi) > 18.5 \) counterparts in the BG LOS. The main exception is that the extent of the coincident absorption region in the J0913-0107 pair.

The absorbers also have high [Zn/H] abundances. After comparing with cosmological simulations, the authors determined that the coincident absorptions are more likely due to groups of two or more galaxies than individual large galaxies.

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log \( N(H_i) = 20.2 \) BG-C component does not correspond to a high \( N(H_i) \) absorption in the FG LOS.

In region A, the dense gas extends more than 90 \( h_{70}^{-1} \) kpc in the transverse direction and 250 km s\(^{-1}\) along the LOS. The components, which have \([O/H] \leq -1.7\) (FG) and \([C/O] \sim [Fe/O] \sim -0.5\) (BG), are consistent with very metal poor gas (Dutta et al. 2013) and approach what is believed to be the IGM metallicity (Simcoe et al. 2004). Each LOS has one strong component in region B. BG-B and FG-B are closely aligned and also have low metal abundances: \([O/H] \leq -1.8\) and -2.0, respectively. Finally, the log \( N(H_i) = 20.2 \) sub-DLA in region C with \([Si/H] = -0.7\) is likely associated with a galaxy. The BG-C abundance is somewhat higher than that of DLAs at the same redshift (Rafelski et al. 2012). If the BG-C sub-DLA galaxy is accreting gas from its surroundings, this could explain the lack of higher column density absorptions in region C of the FG spectrum. Due to accretion, gas in the galaxy halo becomes more sparsely distributed. The A, B, and C regions have distinct properties that are overall consistent in both spectra, but along each LOS the clouds do not appear to be directly in contact.

These absorptions span more than 1 700 km s\(^{-1}\) along each LOS, which corresponds to a proper distance of 6.4 \( h_{70}^{-1} \) Mpc at \( z = 2.69\) (23.6 \( h_{70}^{-1} \) Mpc comoving). Velocity differences at this scale are dominated by the Hubble flow, rather than physical velocities intrinsic to the gas clouds. The A, B, and C absorption regions have a velocity separation of more than 5 000 km s\(^{-1}\) from the FG quasar at \( z = 2.75\), which makes direct association with the quasar environment unlikely (Ellison et al. 2010). In addition to the log \( N(H_i) > 18.0 \) components, several weaker absorptions within the \( \pm 2\) 000 km s\(^{-1}\) region are common to both LOS. Corresponding absorptions with log \( N(H_i) = 14.5 \sim 15.2\) occur near \(-1\) 800 km s\(^{-1}\), -720 km s\(^{-1}\), and \(-450\) km s\(^{-1}\). For Ly\(\alpha\) forest absorptions in the range log \( N(H_i) = 14\) (Ellison et al. 2010) measured a mean line density \( dN/dz = 76.38 \pm 7.32\) for the regions where such Ly\(\alpha\) absorptions can be detected in both LOS cover a total of 950 km s\(^{-1}\). This is less than the full coincident region, since the log \( N(H_i) > 18.0 \) components completely absorb the flux in the remaining portion of the coincident region. The expected number of low column density absorptions is therefore 0.89 \( \pm 0.09\), whereas three are observed. The probability of such an occurrence is only 6%.

To investigate whether the strong absorption systems imply an overdensity, we evaluate the probability of finding two additional LLS within 2 000 km s\(^{-1}\), given that one LLS occurs along the total path length (O’Meara et al. 2013) determined that the line density, \( dN/dz\), for log \( N(H_i) \geq 17.2\) cm\(^{-2}\) absorptions is 0.92 \( \pm 0.18\). For the redshift path between the BG quasar at \( z = 2.916\) and the end of the spectrum at 3 000 Å (\( z = 1.468\)), this probability is \( \sim 0.07%\). Since the LLS absorptions in the J0913-0107 spectrum all have log \( N(H_i) \geq 18.0\), the \( \sim 0.07\%\) probability can be considered an upper limit. The LOS clearly probe an overdense region, which may be evidence of a galaxy protocluster, perhaps with a filamentary structure, or a filament in the IGM. We present arguments for the two interpretations.

Following hierarchical structure formation, regions that give rise to galaxy clusters at \( z < 1\) have been matter-rich throughout cosmic time. In cosmological simulations, individual galaxies come together along gaseous filaments, creating small groups that in turn merge to form clusters by low redshift. Identifying overdense regions at high redshift that will eventually collapse to form gravitationally bound clusters at \( z = 0\) is of particular interest for investigating galaxy cluster evolution. By tracking cluster formation in cosmological simulations, Chiang et al. (2013) were able to predict the \( z = 0\) cluster mass from the galaxy overdensity at \( 2 < z < 5\). The comoving length of the coincident absorption region along the J0913-0107 LOS is consistent with the expected effective diameter for a protocluster. However, to be identified as a protocluster at \( z \sim 2 - 3\) with 80% confidence, a (25 Mpc comoving)\(^3\) region must exhibit an overdensity of more than twice as many galaxies with \( M_i > 10^{9} M_\odot\) than a typical field.

We consider whether it is likely that the absorbers probe gas in the environment of massive galaxies. Rahmati & Schaye (2014) associated log \( N(H_i) > 17\) absorptions with galaxies in cosmological, hydrodynamical simulations (see also McQuinn et al. 2011) at \( z = 3\) and found that most strong absorbers are most closely related to low mass galaxies with \( M_i < 10^{9} M_\odot\). Only log \( N(H_i) > 21\) absorptions are routinely associated with \( M_i > 10^{9} M_\odot\) galaxies. The mass-metallicity relation similarly suggests that typical DLAs have \( M_i > 10^{9} M_\odot\) (Müller et al. 2013). Although the A, B, and C regions in the J0913-0107 LOS are overdense, the galaxies may not be sufficiently massive to directly contribute to the protocluster criterion.

Each quasar LOS can potentially detect C iv gas associated with the circumbulactic medium of massive star-forming galaxies out to a distance of 0.42 \( h_{70}^{-1} \) Mpc comoving (Martin et al. 2010). Combining the Schechter mass function for field galaxies (Tomczak et al. 2014) with the factor of 2.2 overdensity necessary for a galaxy protocluster (Chiang et al. 2013), the LOS probe a volume that would encompass only \( \sim 0.1 M_i > 10^{9} M_\odot\) protocluster galaxies if they are randomly distributed. The possibility that the overdense region intersects a protocluster therefore cannot be ruled out, even if the absorber galaxies are not particularly massive. However, the overdensity of log \( N(H_i) > 18\) absorbers is \( \sim 90\%), which is much higher than the expected overdensity of galaxies in a protocluster. This suggests that the absorbers could be aligned in a filamentary structure.

Cosmic web filaments are expected to consist of clumpy, moderate column density gas distributed over cosmological scales (e.g., Colberg et al. 2005; Cautun et al. 2014; see also...
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