Three-dimensional Distribution Map of HI Gas and Galaxies around an Enormous Lyα Nebula and Three QSOs at z = 2.3 Revealed by the HI Tomographic Mapping Technique

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Abstract

We present an IGM HI tomographic map in a survey volume of 16 × 19 × 131 h⁻³ comoving Mpc³ (cMpc³) centered at MAMMOTH-1 nebula and three neighboring quasars at z = 2.3. The MAMMOTH-1 nebula is an enormous Lyα nebula (ELANE), hosted by a type-II quasar dubbed MAMMOTH1-QSO, that extends over 1 h⁻¹ cMpc with no clear physical origin. Here we investigate the HI-gas distribution around MAMMOTH1-QSO with a large scale of 2.6 h⁻¹ cMpc, it is yet unknown whether or not MAMMOTH1-QSO photoionizes the surrounding HI gas on smaller scales.

1. Introduction

Enormous Lyα nebulae (ELANE) are extremely extended Lyα nebulae discovered around z ~ 2 radio-quiet quasars (e.g., Cantalupo et al. 2014; Cai et al. 2019; Kikuta et al. 2019). Since their Lyα emission exceeds to >1 h⁻¹ comoving megaparsecs (cMpc) beyond the virial diameters of their host quasars, the major origin of ELANE is predicted to be quasar photoionization of neutral hydrogen (H I) gas embedded in the cosmic web (e.g., Cantalupo et al. 2012). However, the gas distribution around ELANE has been poorly investigated in previous studies.

Recently, one of the largest ELANE, MAMMOTH-1, was identified at z = 2.32 by Cai et al. (2017a). MAMMOTH-1 hosts a type-II quasar (hereafter, MAMMOTH1-QSO) and, interestingly, resides in an Lyα emitter (LAE) overdense region that was originally discovered with a strong H I absorber group, dubbed BOSS1441, with multiple background quasar spectra in the Mapping the Most Massive Overdensities through Hydrogen (MAMMOTH) survey (Cai et al. 2017b). Although Cai et al. (2017b) have revealed the existence of the significant H I overdensity around MAMMOTH-1 on a large scale of ~20 h⁻¹ cMpc, it is yet unknown whether or not MAMMOTH1-QSO photoionizes the surrounding H I gas on smaller scales.

To investigate the H I gas distribution on such small scales, one can use galaxies instead of quasars as background sources.
thanks to their higher number densities (e.g., Mawatari et al. 2017; Hayashino et al. 2019). For this purpose, a powerful technique called H1 tomography has been established by Lee et al. (2014a, 2014b). This technique allows us to reconstruct three-dimensional (3D) H1 large-scale structures (LSSs) based on H1 Lyα forest absorption lines detected in background source spectra (see also Lee et al. 2016, 2018).

In this study, we map out the H1 gas distribution around MAMMOTH1-QSO with the H1 tomography technique based on Lyα forest absorption probes with background quasar and galaxy spectra. In addition, by combining results of Lyα forest absorption analyses for background quasars whose projected distances from MAMMOTH1-QSO are relatively large, up to ~200 h⁻¹ cMpc, we estimate the H1 radial profile of MAMMOTH1-QSO over a wide range of scales and make comparisons with quasars at similar redshifts as well as the LAE overdensity distribution.

This paper is organized as follows. In Section 2, we introduce our background source sample and describe the spectroscopic data. In Section 3, our spectral analyses and H1 tomographic reconstruction are described. We present results and discussions in Section 4. Finally, we summarize our findings in Section 5. Throughout this paper, we use a cosmological parameter set (Ω_m, Ω_b, h) = (0.26, 0.74, 0.045, 0.70) consistent with the nine-year WMAP result (Hinshaw et al. 2013). We refer to kpc and Mpc in physical (comoving) units as pkpc and pMpc (kpc and cMpc), respectively. All magnitudes are in AB magnitudes (Oke & Gunn 1983).

2. Data and Sample

To study the H1 gas distribution around MAMMOTH1-QSO over a wide range of scales, we need spectra of background quasars and galaxies. In this section, we construct a spectroscopic sample of background quasars and galaxies around the sky position of MAMMOTH1-QSO. The basic properties of MAMMOTH1-QSO are summarized in Table 1.

2.1. Background Quasars

We select background quasars around MAMMOTH1-QSO from the SDSS DR14 quasar catalog (hereafter DR14Q; Pâris et al. 2018), which includes all quasars identified by the SDSS-IV/eBOSS survey (Myers et al. 2015). The eBOSS spectra have a spectral resolution of R ≡ λ/Δλ ≈ 2000 covering a wavelength range of 3600–10400 Å, which is sufficient for our purpose.

First, we search for quasars in a 6°0×6°0 field around MAMMOTH1-QSO (the 6°0 scale corresponds to a span of 400 h⁻¹ cMpc). We then select quasars whose emission redshifts are in the range of z = 2.4–2.9 so that we can probe Lyα forest absorption lines at the redshift of MAMMOTH1-QSO in the background quasars’ rest-frame 1041–1185 Å spectral region to avoid contamination of H1 Lyα absorption and stellar/interstellar absorption lines associated with the quasar host galaxies (e.g., Mukae et al. 2017). These two criteria yield 240 DR14Q quasars.

To obtain robust measurements of Lyα forest absorption, we check the qualities of the eBOSS spectra and remove quasars whose spectra do not meet additional criteria described below. We require the eBOSS spectra to have a median signal-to-noise ratio (S/N) ≥ 2 over their Lyα forest wavelength range (i.e., 1041–1185 Å in the rest frame). In addition, we remove quasars whose spectra have broad absorption lines by applying BI < 200 km s⁻¹ in the DR14Q catalog, where BI (BALNicity Index) is a measure of the strength of an absorption trough calculated for the CIV emission line. We also remove quasars whose spectra show damped Lyα systems (DLAs) in the Lyα forest wavelength range, based on the DLA catalog of Noterdaeme et al. (2012) and their updated one20 for the SDSS DR12 quasars (Pâris et al. 2017). For quasars that have no SDSS DR12 counterpart, we visually inspect the eBOSS spectra and remove them if they show signatures of DLAs in their Lyα forest wavelength range. Our careful selection results in a sample of 117 background quasars for our subsequent analyses.

For convenience, we divide the 6°0×6°0 field around MAMMOTH1-QSO into three regions, BQ1, BQ2, and BQ3 as illustrated in Figure 1. The boundary between BQ1 and BQ2 is defined with a rectangle whose corners are (ΔRA, Δdecl.) = (−0°.19, −0°.21), (−0°.19, +0°.058), (+0°.11, +0°.058), and (+0°.11, −0°.21) relative to the coordinate of MAMMOTH1-QSO, so that the 16 h⁻¹ cMpc × 19 h⁻¹ cMpc area of the BQ1 region can cover the position of MAMMOTH1-QSO as well as the LAE overdense region for comparison in Section 4.3.

The boundary between BQ2 and BQ3 is defined with a rectangle whose corners are ΔRA, = ±0°4 and Δdecl. = ±0°3. This corresponds to a 40 h⁻¹ cMpc × 41 h⁻¹ cMpc rectangle atop the entire BOSS1441 field (Cai et al. 2017b). In the BQ1, BQ2, and BQ3 regions, the numbers of our background quasars are 1, 4, and 112, respectively. The distributions of the background quasars in BQ1 and BQ2 regions are presented in Figure 1. The basic properties of the background quasars in the BQ1 and BQ2 regions are provided in Tables 2 and 3, respectively.

Note that Cai et al. (2017b) have identified the strong H1 absorber group based on the spectra of these five background quasars as well as an additional one in the BQ1–2 regions. In our analyses we do not use the spectrum of the additional quasar, since its redshift is z > 2.9 and there is a possibility that the spectrum is contaminated by the Lyβ absorption and/or stellar/interstellar absorption due to the quasar host galaxy.

\[^{20}\text{http://www2.iap.fr/users/noterdae/DLA/DLA.html}\]

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### Table 1

| Source         | R.A. (J2000) | Decl. (J2000) | z_{spec} | V (mag) | Reference^a |
|----------------|--------------|--------------|----------|--------|-------------|
| MAMMOTH1-QSO   | 14 41 24.46^b| +40 03 09.20^b| 2.319    | 24.20  | C17         |

**Notes.**

^a C17: Cai et al. (2017a).

^b Updated coordinates in Keck/KCWI observations of Z. Cai et al. (2020, in preparation).
Table 2
Background Objects for H I Tomographic Reconstruction in the BQ1 Region

| Source          | R.A. (J2000) | Decl. (J2000) | z spec | g (AB) | V (AB) | Exposure | Time (s) | Sample^a |
|-----------------|--------------|---------------|--------|--------|--------|----------|----------|----------|
| BQ1-5172-56071-0534 | 14 40 48.56  | +39 56 18.39  | 2.543  | 20.04  | ...    | ...      | ...      | eBOSS    |
| 20170827_M1_05   | 14 41 19.44  | +39 59 49.52  | 2.509  | ...    | 24.04  | 9000     | 20160405_M2_35 | LRISs    |
| 20170827_M1_07   | 14 41 26.77  | +39 59 25.01  | 2.816  | ...    | 23.40  | 9000     | 20160405_M2_27 | LRISs    |
| 20170827_M2_22   | 14 41 27.98  | +40 03 43.31  | 2.510  | ...    | 24.50  | 9000     | 20160405_M2_08 | LRISs    |
| 20170827_M1_24   | 14 41 30.05  | +40 04 05.59  | 2.671  | ...    | 23.58  | 9000     | 20160510_M2_25 | LRISs    |
| 20160510_M2_05   | 14 41 11.50  | +39 57 24.08  | 2.546  | ...    | 24.11  | 5400     | 20160510_M2_10 | LRISs    |
| 20160510_M2_10   | 14 41 16.63  | +39 58 51.56  | 2.598  | ...    | 23.21  | 5400     | 20160510_M2_26 | LRISs    |
| 20160510_M2_25   | 14 41 34.49  | +40 00 58.68  | 2.795  | ...    | 23.61  | 5400     | 20160509_M1_11 | LRISs    |
| 20160509_M1_11   | 14 41 40.29  | +40 00 46.08  | 2.557  | ...    | 23.05  | 4000     | 20160509_M1_23 | LRISs    |
| 20160509_M1_23   | 14 41 38.31  | +40 04 23.49  | 2.786  | ...    | 22.84  | 4000     | 20160405_M1_05 | LRISs    |
| 20160405_M1_05   | 14 41 25.85  | +40 01 31.40  | 2.795  | ...    | 22.82  | 6000     | 20160405_M2_08 | LRISs    |
| 20160405_M2_08   | 14 41 10.15  | +39 52 28.88  | 2.791  | ...    | 24.27  | 6000     | 20160405_M2_10 | LRISs    |
| 20160405_M2_10   | 14 41 15.62  | +39 55 43.97  | 2.512  | ...    | 24.42  | 6000     | 20160405_M2_11 | LRISs    |
| 20160405_M2_11   | 14 41 08.38  | +39 52 15.59  | 2.497  | ...    | 23.68  | 6000     | 20160405_M2_20 | LRISs    |
| 20160405_M2_20   | 14 40 56.98  | +39 54 03.24  | 2.703  | ...    | 24.34  | 6000     | 20160405_M2_27 | LRISs    |
| 20160405_M2_27   | 14 40 55.13  | +39 55 25.70  | 2.840  | ...    | 24.37  | 6000     | 20160405_M2_35 | LRISs    |
| 20160405_M2_35   | 14 40 45.31  | +39 55 35.76  | 2.598  | ...    | 23.07  | 6000     |                     | LRISs    |

Note.

^a eBOSS: eBOSS spectroscopy data (Section 2.1), LRISs: Keck spectroscopy data (Section 2.2.2). LRISa: Keck archive data (Section 2.2.3).

For this purpose, we produce a multiwavelength catalog across the BQ1 region based on optical (U, V, and i) and near-IR (J and H) imaging data obtained by Cai et al. (2017b) and Z. Cai et al. (2020, in preparation) with the Large Binocular Camera (LBC; Pedichini et al. 2003) on the Large Binocular Telescope (LBT) and the Wide Field Camera (WFCAM; Casali et al. 2007) on the United Kingdom Infrared Telescope (UKIRT), respectively. We match the point-spread functions (PSFs) of these images to that of the H-band image whose FWHM (0.9″) is the largest among them. The 5σ limiting magnitudes in the U, V, i, J, and H bands measured with 2″ diameter apertures are 26.6, 26.2, 26.1, 23.7, and 23.1 mag, respectively. We then create a multiwavelength source catalog by running SExtractor (Bertin & Arnouts 1996) in dual image mode. Colors of the detected sources are measures with 2″ diameter apertures.

Based on the multiwavelength catalog, we estimate photometric redshifts of the detected sources to select background galaxy candidates at z = 2.4–2.9. First of all, we apply a magnitude cut of V < 24.85 mag so that we can select background galaxy candidates whose continuum emission can be detected with sufficiently high S/Ns in subsequent spectroscopic observations. We then estimate their photometric redshifts with the EAZY software (Brammer et al. 2008) by fitting spectral energy distribution (SED) templates to the observed photometric data points. The SED templates are produced with the stellar population synthesis model of Bruzual & Charlot (2003). We adopt the Chabrier initial mass function (Chabrier 2003), a constant star formation for 0.1 Gyr, and a fixed metallicity of Z = 0.2Z⊙. The metallicity is chosen to be close to the metallicity estimates of star-forming galaxies in Pettini et al. (2000, 2001). We apply the Calzetti dust attenuation (Calzetti et al. 2000) with E(B − V) = 0.0, 0.15, 0.30, and 0.45. We also apply attenuation by IGM absorption with a model of Inoue et al. (2014). We require background galaxy candidates to have a photometric redshift whose 1σ confidence interval is within the redshift range of z = 2.4–2.9. The 1σ errors on the photometric redshift from the used software are ~0.17. This selection yields a sample of 131 background galaxy candidates in BQ1.

Figure 1. Sky distribution of our background quasars and galaxies in the BQ1 and BQ2 regions. The blue diamonds (stars) represent the positions of our background quasars (galaxies) at z = 2.4–2.9. The gray diamond indicates a z > 2.9 quasar that is used in Cai et al. (2017b) in addition to the other five quasars, although we do not use it in our analyses (for details, see Section 2.1). The double square is the position of MAMMOTH1-QSO at z = 2.32 and the single squares are those of three neighboring quasars at z = 2.3, QSOs 1–3 (Section 4.2.2). The dark gray dots are z = 2.32 LAEs found in the previous work (Cai et al. 2017b), whose survey area is shown with light gray dashed lines. The color contours represent LAE overdensities Δ_{\text{LAE}} calculated in Section 4.3.

2.2. Background Galaxies

2.2.1. Candidate Selection

As shown in Figure 1, the number of our background quasars near MAMMOTH1-QSO is small, only one in the BQ1 region. To investigate the Hi gas distribution around MAMMOTH1-QSO down to a small scale, we need a sample of close background galaxies at z = 2.4–2.9 near MAMMOTH1-QSO.
Table 3

| Source                  | R.A. (J2000) | Decl. (J2000) | zspec | g  | Reference |
|------------------------|--------------|--------------|-------|----|-----------|
| BQ2-5171-56038-0020    | 14 39 58.45  | +40 03 13.99 | 2.422 | 20.20 | DR14Q    |
| BQ2-8498-57105-0478    | 14 41 59.76  | +39 55 25.32 | 2.546 | 19.47 | DR14Q    |
| BQ2-5172-56071-0616    | 14 42 10.56  | +39 56 31.92 | 2.612 | 20.99 | DR14Q    |
| BQ2-5172-56071-0608    | 14 42 51.84  | +40 14 53.52 | 2.547 | 20.86 | DR14Q    |

Note.

* DR14Q: Pâris et al. (2018).

2.2.2. Follow-up Spectroscopy

We carried out spectroscopic observations for our background galaxy candidates using the Low Resolution Imaging Spectrometer (LRIS) Double-Spectrograph (Oke et al. 1995) on the Keck I telescope on 2017 August 27 (UT) (PI: S. Mukae). We used the d560 dichroic with the B600/4000 grism on the blue arm, resulting in a wavelength coverage of 3800–5500 Å. The observations were made in the multi-object slit (MOS) mode. We designed one mask targeting background galaxy candidates around MAMMOTH1-QSO with 1″0 slit width, yielding a spectroscopic resolution of \( R = \lambda / \Delta \lambda \approx 1000 \). We select 25 background galaxies from our 131 background galaxy candidates based on photometric redshift probability, source brightness, and uniformity on the sky. The total exposure time was 9000 s. The sky conditions were clear throughout the observing run, with an average seeing size of 0′′95.

We reduce the LRIS data with the Low-Redux package\(^{21}\) in the public XIDL pipeline.\(^{22}\) The pipeline conducts bias subtraction, flat-fielding with dome flat and twilight flat data, wavelength calibration with arc data, cosmic-ray rejection, source identification, spectral trace determination, sky background subtraction, and distortion correction. We then extract one-dimensional (1D) spectra of the identified sources from the reduced two-dimensional (2D) spectra and combine them to obtain their stacked 1D spectra.

2.2.3. Archival Search

In addition to our own observations, two other LRIS programs were conducted for the BOSS1441 field in the MOS mode on 2016 April 5 (UT) (PI: X. Fan) and 2016 May 9–10 (UT) (PI: X. Prochaska) by using the same dichroic and grism as ours. Although the original aim of their LRIS programs is to identify associated galaxies in the BOSS1441 overdense region at \( z = 2.32 \) (Z. Cai et al. 2020, private communication), there is a possibility that some background galaxies at \( z = 2.4–2.9 \) are included as targets in the MOS masks and spectroscopically identified by chance. Thus, we download raw LRIS data obtained in the two programs from the Keck Observatory Archive (KOA)\(^{23}\) and reduce them in the same manner as for our LRIS data.

2.2.4. Sample Construction for Our Analyses

We determine spectroscopic redshifts (\( z_{\text{spec}} \)) of the observed sources based on the LRIS spectra obtained in Sections 2.2.2 and 2.2.3. We fit the galaxy spectrum template of Shapley et al. (2003) to the LRIS spectra and determine the best-fit \( z_{\text{spec}} \) by the minimum value of \( \chi^2 \). We find that 20 galaxies have \( z_{\text{spec}} \) values in the range of 2.4–2.9.

To obtain robust measurements of Ly\( \alpha \) forest absorption, in the same way as for the background quasars, we further require that the spectra of background galaxies have a median \( S/N \geq 2 \) in the Ly\( \alpha \) forest wavelength range of 1041–1185 Å in the rest frame. In addition, based on our visual inspection, we remove a galaxy whose spectrum shows a possible feature of a DLA in the Ly\( \alpha \) forest wavelength range. These selections result in a sample of 16 background galaxies. The basic properties of the 16 background galaxies in the BQ1 region are summarized in Table 2.

Figure 2 shows the positions of the background quasar and galaxies in the BQ1 region. The mean (median) transverse sightline separation is \( \langle d_s \rangle = 2.6 \) (2.7) h\(^{-1}\) Mpc, which is comparable to that of the H\( \text{I} \) tomographic map of Lee et al. (2014b). The filling factor of the sky coverage, which is defined as the fraction of the regions around the sightlines of the background sources within \( \langle d_s \rangle \) in the BQ1 region, is about 0.45.

3. Analysis

3.1. Ly\( \alpha \) Forest Transmission

To measure the strengths of Ly\( \alpha \) forest absorption around MAMMOTH1-QSO along the lines of sight to the background quasars and galaxies, we estimate the Ly\( \alpha \) forest transmission,

\[
F(\alpha) = \frac{f_{\text{obs}}}{f_{\text{int}}} \tag{1}
\]

where \( \alpha \) is the Ly\( \alpha \) absorber redshift derived from the observed wavelength \( \lambda_{\text{obs}} \) (i.e., \( \lambda_{\text{obs}}/1216\text{Å}-1 \)), \( f_{\text{obs}} \) is the observed continuum flux density, and \( f_{\text{int}} \) is the intrinsic continuum flux density that is not affected by the Ly\( \alpha \) forest absorption due to the IGM. The transmission \( F(\alpha) \) is computed pixel by pixel with a pixel scale of 0.8 (1.2) Å for our eBOSS (LRIS) spectra.

We estimate \( f_{\text{int}} \) based on the spectra of the background quasars and galaxies in the BQ1–3 regions by applying the mean flux regulated principal component analysis (MF-PCA) continuum fitting technique (Lee et al. 2012) with the code developed by Lee et al. (2013; see also Lee et al. 2014b). This technique is composed of two steps. The first step is to fit spectral templates of quasars and galaxies with the observed spectra redward of Ly\( \alpha \) to obtain initial guesses of their continuum spectra blueward of Ly\( \alpha \). We use the spectral templates of quasars and galaxies constructed by Suzuki et al. (2005) and Berry et al. (2012), respectively. The second step is to further adjust the continuum spectra by multiplying and fitting a linear function, \( a_{\text{MF}} + b_{\text{MF}} \lambda_{\text{rest}} \), where \( a_{\text{MF}} \) and \( b_{\text{MF}} \) are free parameters for the fit, and \( \lambda_{\text{rest}} \) is the rest-frame
spectra are shown in Figure 3. Although the MF-PCA continuum estimates for our background quasar and galaxy 
uncertainties of conservative estimates in the following analyses. The uncertainties in the wavelength range could bias the results, we do not use the 
continuum, the discontinuity does not affect our analysis in the 
Figure 2. Sky distribution of our background sources in the BQ1 region. The blue diamond and stars represent the positions of our background quasar and galaxies, respectively. The white area highlights regions around the sightlines around the background sources within the mean transverse sightline separation ($d_t = 2.6 h^{-1}$ Mpc). The double square denotes the position of MAMMOTH1-QSO and the single squares show those of three neighboring quasars, QSOs 1–3 (Section 4.2.2). The top and right axes are comoving separations relative to the bottom right corner coordinate of the BQ1 region, (R.A., decl.) = (220°16, 39°84).

wavelength. This fit is performed for the continuum spectra within the Ly$\alpha$ forest wavelength range of 1041–1185 Å in the rest-frame to yield a mean transmission (using Equation (1)) consistent with previous measurements of the cosmic mean Ly$\alpha$ forest transmission, $F_{\cos}(z)$. We adopt $F_{\cos}(z)$ estimated by Faucher-Giguère et al. (2008),

$$F_{\cos}(z) = \exp[-0.00185(1 + z)^{3.92}],$$

where $z$ is the Ly$\alpha$ absorber redshift. Both the examples of continuum estimates for our background quasar and galaxy spectra are shown in Figure 3. Although the MF-PCA technique introduces a discontinuity at 1185 Å in the final continuum, the discontinuity does not affect our analysis in the Ly$\alpha$ forest wavelength range blueward of 1185 Å (see Lee et al. 2012, 2013 for more details).

There is a possibility that the strong H$\text{i}$ absorption group at $z = 2.32 \pm 0.03$ found by Cai et al. (2017b) could bias the intrinsic continuum estimate. To avoid possible contamination of their strong Ly$\alpha$ absorption, we mask out the wavelength range of 4036 ± 36 Å in the MF-PCA fitting.

We then obtain $F(z)$ by using Equation (1). Since the strong stellar and interstellar absorption lines of N$\text{II}$ λ1084 and C$\text{III}$ λ1175 associated with background sources in the Ly$\alpha$ forest wavelength range could bias the results, we do not use the spectra in the wavelength ranges of ±5 Å around these lines for conservative estimates in the following analyses. The uncertainties of $F(z)$ are calculated from the uncertainties of the $f_{\text{obs}}$

measurements and the $f_{\text{int}}$ estimates based on the MF-PCA continuum fitting, the latter of which are evaluated by Lee et al. (2012) as a function of redshift and median S/N over the Ly$\alpha$ forest wavelength range (see their Figure 8). Specifically, we adopt MF-PCA continuum fitting errors of 7%, 6%, and 4% for spectra with median S/Ns over the Ly$\alpha$ forest wavelength range of 2–4, 4–10, and >10, respectively.

Based on the estimated $F(z)$ and the cosmic mean Ly$\alpha$ forest transmission $F_{\cos}(z)$, we calculate the H$\text{i}$ overdensity $\delta_F$, following the definition introduced by Lee et al. (2014a, 2014b),

$$\delta_F = \frac{F(z)}{F_{\cos}(z)} - 1,$$

where negative values correspond to strong H$\text{i}$ Ly$\alpha$ absorption. The uncertainties of $\delta_F$ are calculated based on the uncertainties of $F(z)$. We confirm that a systematic effect of using different prescriptions of $F_{\cos}(z)$ obtained by Becker et al. (2013) and Inoue et al. (2014) is minor, only within 2%, which is not as large as the uncertainties of $F(z)$.

3.2. H$\text{i}$ Tomographic Reconstruction

For the BQ1 region, where the background sightline density is high, we carry out an H$\text{i}$ tomographic reconstruction to reveal the 3D distribution of H$\text{i}$ gas near MAMMOTH1-QSO with the code
developed by Stark et al. (2015). The reconstruction code performs the Wiener filtering for the estimated \( \delta_F \) values along the sightlines of our background quasar and galaxies. The Wiener filtering is based on a Gaussian smoothing with the scale of \((d_e,\) which determines the spatial resolution of our tomographic map. We adopt a grid size of \(0.5 h^{-1} \) cMpc, which is sufficiently small compared to \((d_e,\) We choose a redshift range of \(z = 2.25-2.40\) that covers a large distance of \(\sim \pm 65 h^{-1} \) cMpc from MAMMOTH1-QSO at \(z = 2.32\) in the redshift direction, giving an overall volume of \(16 \times 19 \times 131 h^{-3} \) cMpc\(^3\). More details about the reconstruction process is provided by Stark et al. (2015) and Lee et al. (2018).

There is a possibility that sightlines used in the H\(\text{I}\) tomography could undersample small H\(\text{I}\) gas clumps in the Ly\(\alpha\) forest on scales below \((d_e,\) We thus do not use the small-scale gas distributions in our discussions from Section 4.1. The simulation studies of Lee et al. (2014a) demonstrated that an H\(\text{I}\) tomography pixel could have the \(\delta_F\) error of \(\lesssim 0.05\) due to the small-scale undersampling of the Ly\(\alpha\) forest.

Note that we do not reconstruct H\(\text{I}\) tomographic maps for the BQ2-3 regions due to the coarse sightline distributions whose sightline separations are \(\sim 15-20 h^{-1} \) cMpc. Instead, we use the BQ2-3 background quasars for large-scale \(\delta_F\) measurements along the sightlines (Section 4.2).

4. Results and Discussion

4.1. H\(\text{I}\) Tomographic Map

Figure 4 presents the resulting H\(\text{I}\) tomographic map for the BQ1 region. Our tomographic map shows \(\delta_F\) values in the range of \(-0.6 < \delta_F < 0.4\), revealing the existence of H\(\text{I}\) overdense \((\delta_F \simeq -0.3 - (-0.2))\) and underdense \((\delta_F \simeq 0.3 - 0.2)\) LSSs with sizes of 10–20 \(h^{-1} \) cMpc around MAMMOTH1-QSO for the first time. In this region, the strong H\(\text{I}\) absorption group at \(z = 2.32\) has been found in the previous work based on only the six background quasar spectra (Cai et al. 2017b) as mentioned in Section 2.1. Thanks to the higher sightline density of our background source sample in this field, our results unveil the inhomogeneous distribution of H\(\text{I}\) gas around MAMMOTH1-QSO.

4.2. H\(\text{I}\) Radial Profile

4.2.1. H\(\text{I}\) Gas around MAMMOTH1-QSO

In the BOSS1441 region, there is a type-II quasar dubbed MAMMOTH1-QSO that has one of the largest ELANe, MAMMOTH-1 nebula at \(z = 2.32\) (Cai et al. 2017a). Since the Ly\(\alpha\) emission spatially extends to \(>1 h^{-1} \) cMpc beyond the virial diameter of the host quasar, the origin of MAMMOTH-1 nebula is thought to be the quasar photoionization of the H\(\text{I}\) gas cloud embedded in the cosmic web (e.g., Cantalupo et al. 2012). Thus, the H\(\text{I}\) absorption around the MAMMOTH1-QSO is expected to be suppressed.

We derive the radial profile of H\(\text{I}\) overdensity \(\delta_F\) around MAMMOTH1-QSO (hereafter H\(\text{I}\) radial profile). Within the BQ1 region, we use the H\(\text{I}\) tomographic map to calculate spherically averaged \(\delta_F\) as a function of the 3D distance from MAMMOTH1-QSO, which is defined as

\[
R_{3D} = \sqrt{d_{R.A.}^2 + d_{decl.}^2 + d_z^2}.
\]

\(d_{R.A.}\), \(d_{decl.}\), and \(d_z\) are the comoving distances from MAMMOTH1-QSO under the assumption that the H\(\text{I}\) absorbers have zero peculiar velocities relative to MAMMOTH1-QSO.

To estimate the uncertainties of the spherically averaged \(\delta_F\) values, we create mock Ly\(\alpha\) forest transmission data by adding
noise to the obtained $F(z)$ data based on the uncertainties of $F(z)$ estimated in Section 3.1, and calculate the $\delta_F$ values for the mock data along the 17 sightlines. We then obtain a mock H I tomographic map, and compute spherically averaged $\delta_F$ values as a function of $R_{3D}$. We repeat this process 1000 times and obtain 68% intervals as the 1σ confidence intervals. Note that the typical 1σ uncertainty of $\delta_F$ for a pixel in the H I tomographic map is found to be about 0.08.

The H I tomographic map allows us to obtain the H I radial profile up to around $R_{3D} = 6$ pMpc, which is limited due to the size of our H I tomographic map. To extend our measurements beyond 6 pMpc, we obtain spherically averaged $\delta_F$ values based on the $\delta_F$ measurements along the sightlines of the background quasars in the BQ2–3 regions. Thanks to the large field coverage, our H I radial profile measurements probe up to about 100 pMpc around MAMMOTH1-QSO.

Figure 5 shows the obtained H I radial profile around MAMMOTH1-QSO. We find that $\delta_F$ decreases (i.e., the strength of H I absorption increases) with increasing $R_{3D}$ up to $\approx$ 3 pMpc from $\delta_F \approx 0$ to $\delta_F = -0.06 \pm 0.02$, and $\delta_F$ slightly increases at larger distances. In other words, the H I radial profile of MAMMOTH1-QSO shows a possible turnover at $R_{3D} \approx 3$ pMpc, indicating that MAMMOTH1-QSO resides in a volume with fairly weak H I absorption. This tendency at small distances is opposite to that found for moderately bright galaxies at similar redshifts (e.g., Rakic et al. 2012; Rudie et al. 2012; Turner et al. 2014); the H I gas absorption around galaxies is stronger at smaller galactocentric radii. Our results may suggest that MAMMOTH1-QSO has a proximity zone where H I gas is photoionized and H I absorption is suppressed due to strong ionizing radiation from MAMMOTH1-QSO. In this picture, the ELAN around MAMMOTH1-QSO may be a photoionized cloud embedded in the cosmic web.

We caution readers that our suggested picture is based on the tomographic map data as well as the background sources, which are partially sampling the space around MAMMOTH1-QSO (see Figures 1 and 2). Although we find a possible turnover in the H I radial profile, the validity of this picture should be statistically tested with more background sources in future work.

Note that the H I radial profile shows negative $\delta_F$ values at $R_{3D} \approx 10–30$ pMpc, which is consistent with the detection of the strong H I absorption group found by Cai et al. (2017b). We also confirm that the $\delta_F$ values reach the cosmic average ($\delta_F = 0$) at a large scale of $R_{3D} \approx 100$ pMpc.

4.2.2. Comparisons with Type-I Quasars

Since MAMMOTH1-QSO is categorized as a type-II quasar (Cai et al. 2017a), it is interesting to compare its H I radial profile with those of type-I quasars.

To make comparisons with type-I quasars, we select three type-I quasars (QSO1, QSO2, and QSO3) within our H I tomographic map from the DR14Q catalog and calculate spherically averaged H I radial profiles around them in the same manner as that for MAMMOTH1-QSO. The basic properties of QSOs 1–3 are summarized in Table 4 and their positions in the tomographic map are shown in Figure 4.

Figure 6 compares the H I radial profiles of QSOs 1–3 with that of MAMMOTH1-QSO. We find that their H I radial profiles are similar to that of MAMMOTH1-QSO across 100 pMpc, showing a common turnover at $R_{3D} \approx 3$ pMpc. We should be cautious of the partial sampling around QSOs 1–3 (see Section 4.2.1). This result may indicate that spherically averaged H I gas distributions around type-I and type-II quasars are similar, which is compatible with the AGN unification model (e.g., Antonucci 1993; Elvis 2000): type-I quasars can ionize gas preferentially in the line-of-sight direction, while

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25 MAMMOTH1-QSO is not observed in the eBOSS survey because of its faintness ($V = 24.20$ mag).
type-II quasars can ionize gas in the transverse directions rather than the line-of-sight direction.

Figure 7 presents 2D slices of the HI tomographic map projected across $2.6 h^{-1}$ cMpc along the x (R.A.) direction around QSOs 1–3 and MAMMOTH1-QSO. The projected ranges along the x direction for the four slices are shown in Figure 8. In Figure 7, we find that both QSOs 1–3 and MAMMOTH1-QSO are associated with or surrounded by HI underdense regions with sizes of $\approx 5-10 h^{-1}$ cMpc, which would be created by strong photoionizing radiation from the quasars. Interestingly, these sizes are comparable to the estimated sizes of proximity zones of $z \approx 2$ quasars (D’Odorico et al. 2008).

Note that there is a representative of HI absorption measurements as a function of transverse distances to $z \approx 2$ type-I quasars performed by Prochaska et al. (2013), who have made use of a large ensemble of foreground/background quasar pairs based on the Quasar Probing Quasar survey (hereafter QPQ6). We estimate HI absorption around MAMMOTH1-QSO and QSOs 1–3 with the same method as used in QPQ6, and present comparisons with the QPQ6 results in the Appendix. We could not investigate HI gas distributions at

![Figure 7. Projections of our HI tomographic map across $2.6 h^{-1}$ cMpc slices in the R.A. direction centered at the positions of MAMMOTH1-QSO and QSOs 1–3 from top to bottom. The projected R.A. ranges are shown in Figure 8. The color contours represent the HI overdensity $\delta_F$ such that negative values (red) correspond to higher overdensities. The double square indicates the position of MAMMOTH1-QSO, and the single squares show QSOs 1–3. The two vertical lines at $z \approx 2.30$ and $z \approx 2.33$ denote the redshift range where Ly$\alpha$ emission can be probed with NB403 used in Cai et al. (2017a, 2017b; see Section 4.3).](#)

![Figure 8. Projection of the HI tomographic map over the redshift range of $z = 2.30-2.33$. The color contours represent the projected $\delta_F$. The gray dots are the LAEs found by Cai et al. (2017b) and the gray contours represent the significances of the LAE overdensities from $2\sigma$ to $6\sigma$. The LAE distribution shows two density peaks that are marked with purple crosses. The double square indicates the position of MAMMOTH1-QSO and the single squares are those of the three neighboring type-I quasars. The red bars X0–X3 correspond to the R.A. ranges adopted for the slices in Figure 7.](#)
small scales of \( R_{3D} \lesssim 1 \) pMpc where the QPOQ study probes because of the small number of background sightlines close to the quasars and thus the large uncertainties. The detailed comparison will be conducted with future dense sampling of background sightlines at small scales of \( R_{3D} \lesssim 1 \) pMpc.

### 4.3. LAE-H I Overdensity

As described in Section 1, the LAE overdense region has been found around MAMMOTH1-QSO in previous narrow-band (NB403) imaging observations (Cai et al. 2017b). Since galaxies are good tracers of LSSs of the matter distribution in the universe, it is interesting to compare the spatial distribution of LAE overdensities with that of H I overdensities.

We compute the LAE overdensity based on the LAE sample constructed by Cai et al. (2017b).\(^{26}\) The LAE overdensity \( \delta_{\text{LAE}} \) is defined as

\[
\delta_{\text{LAE}} \equiv \frac{n_{\text{LAE}}}{\bar{n}_{\text{LAE}}} - 1,
\]

where \( n_{\text{LAE}} \) and \( \bar{n}_{\text{LAE}} \) are the LAE number density and its average, respectively, measured in a cylinder with a radius of \( \langle d_{r} \rangle \simeq 2.6 \) h\(^{-1}\) cMpc. For the cylinder length along the \( z \) direction, we adopt a length of \( \simeq 32.4 \) h\(^{-1}\) cMpc that corresponds to the redshift range where Ly\( \alpha \) emission can be detected within the FWHM of NB403, i.e., \( z = 2.30-2.33 \). The obtained LAE overdensity is presented in Figure 1. We find two LAE LSSs whose density peaks are located at (R.A., decl.) = (14:41:27.12, +40:02:00.6) and (14:41:07.84, +39:55:22.8).

In Figure 8, we compare the sky distribution of the LAE overdensity with the projected H I overdensity over the same redshift range of \( z = 2.30-2.33 \) calculated from the H I tomographic map. We find that the two LAE density peaks are spatially offset from the H I density peaks by \( \sim 3-5 \) h\(^{-1}\) cMpc. It is thought that galaxies are good tracers of underlying gas and dark matter distributions. However, since LAEs are star-forming galaxies and can emit ionizing photons, the H I gas near the LAE density peaks would be relatively easily photoionized compared to LAE underdense regions. Such an anisotropic ionizing background radiation created by the density fluctuations of star-forming galaxies may cause this segregation between LAEs and H I LSSs.

Another interesting point in Figure 8 is that the two LAE overdense structures are bridged by one of the H I overdense structures. This would be consistent with the picture that galaxy overdense structures are connected by the H I cosmic web.

We also find that the position of MAMMOTH-1 is located around the edges of the LAE overdense region and the H I overdense region. In previous studies, LAEs with extended Ly\( \alpha \) emission at similar redshifts tend to locate around the edges of galaxy overdense regions rather than the density peaks (Mawatari et al. 2012; Bădescu et al. 2017). Our results are consistent with these previous results.

### 5. Conclusion

We have investigated the 3D distribution of IGM H I gas around the ELAN of MAMMOTH-1 at \( z = 2.3 \). In a volume of \( 16 \times 19 \times 131 \) h\(^{-3}\) cMpc\(^3\) around MAMMOTH1-QSO, we have constructed an H I tomographic map based on Ly\( \alpha \) forest absorption detected in one eBOSS quasar and 16 Keck/LRIS galaxy spectra. By combining the H I tomographic map results with H I overdensity estimates based on background quasar spectra in the outer region, we have derived a spatially averaged H I radial profile of MAMMOTH1-QSO over a wide range of scales from about 0.1 pMpc to 100 pMpc. Our results are summarized below.

1. The IGM H I tomographic map reveals the existence of H I overdense (\( \delta_{z} \simeq -0.3 \)) and underdense (\( \delta_{z} \simeq 0.3 \)) LSSs with the size of \( 10-20 \) h\(^{-1}\) cMpc for the first time, indicating that the H I gas distribution around MAMMOTH1-QSO is inhomogeneous.

2. The H I radial profile of MAMMOTH1-QSO has a possible turnover at \( R_{3D} \simeq 3 \) pMpc and may increase with decreasing \( R_{3D} \), suggesting that MAMMOTH1-QSO may have a proximity zone where the quasar photoionizes the surrounding H I gas and suppresses H I absorption. The MAMMOTH-1 Ly\( \alpha \) nebula is probably a photoionized cloud embedded in the cosmic web.

3. The H I radial profile of MAMMOTH1-QSO, which is a type-II quasar, is similar to those of neighboring three type-I quasars at similar redshifts. This result suggests that spatially averaged H I gas distributions around type-I and type-II quasars are similar, which is compatible with the AGN unification model.

4. Based on a comparison between the H I overdensity map and the distribution of LAEs around MAMMOTH1-QSO, we have found that their density peaks are spatially offset by about \( 3-5 \) h\(^{-1}\) cMpc. This spatial offset between the H I and LAE LSSs may reflect anisotropic UV background radiation created by star-forming galaxy density fluctuations in this field.

The connection between IGM H I and galaxy formation in LSSs can be systematically explored by a wide-field spectroscopic survey of the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX; Hill & HETDEX Consortium 2016). The HETDEX survey will provide \( 10^6 \) LAEs at \( z \sim 2-3 \) over 400 deg\(^2\), and reveal a number of extended Ly\( \alpha \) nebulae and LSSs such as overdensities and filaments. The LSS/IGM study with HETDEX will be complementary to the ongoing program of CLAMATO (Lee et al. 2018), MAMMOTH (Cai et al. 2016), and the planned program of gigantic IGM tomographic mapping with Subaru/PFS (K. Nagamine et al. 2020, in preparation).

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\(^{26}\) The detection limit of their observations corresponds to a Ly\( \alpha \) luminosity of \( \sim 0.73L_{\text{Ly}\alpha} \), where \( L_{\text{Ly}\alpha} = 2.14 \times 10^{42} \) erg s\(^{-1}\) is the characteristic Ly\( \alpha \) luminosity at \( z = 2.1-3.1 \) (Ciardullo et al. 2012).
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Appendix

H 1 Absorption as a Function of Transverse Distances

In this appendix, we estimate H 1 absorption around MAMMOTH1-QSO and QSOs 1–3, and compare with the QPQ6 results (Prochaska et al. 2013). We use our background source spectra, and apply the same method as used in QPQ6 (hereafter R 2D measurements) in which we take average of H 1 absorption in a ±1000 km s −1 velocity window around the QSOs as a function of transverse distances to the quasars (R 2D). The results for MAMMOTH1-QSO and QSOs 1–3 are shown in Figure A1. We find that our H 1 absorption estimates are largely consistent with the QPQ6 result at R 2D > 0.6 pMpc (=1.3 h −1 cMpc) that

![Figure A1](image)

*Figure A1. H 1 absorption around MAMMOTH1-QSO and QSOs 1–3 estimated with the R 2D measurements. The (gray, deep pink, light green, and navy) squares are R 2D measurements around (MAMMOTH1-QSO, QSO1, QSO2, and QSO3) in the BQ1 and BQ2 regions. Red squares are the results of QPQ6 (Prochaska et al. 2013). The (black, magenta, green, and blue) circles are H 1 radial profiles of (MAMMOTH1-QSO, QSO1, QSO2, QSO3) shown in Figures 5 and 6. The horizontal dotted line represents the cosmic average of the H 1 absorption at z = 2.32.*
corresponds to half the mean transverse sightline separation ($d_t$). We could not probe at $R_{2D} < 0.6$ pMpc because of the small number of background sightlines close to the quasars and thus the large uncertainties. In Figure A1, we also show our H I radial profiles (Section 3.2) to compare with the $R_{2D}$ measurements. We should be cautious about this comparison, because the $R_{2D}$ measurements probe the H I absorption only in the transverse directions to the quasars while the H I radial profiles are calculated with spherically averaged H I overdensities, allowing us to probe the H I radial profile averaged over all directions. Nevertheless, we find the possible turnovers at $\simeq 3$ pMpc in both the measurements, which could support our argument of proximity zones in Section 3.2. Since the data points of the H I radial profiles below 0.6 pMpc can be affected by interpolation in the tomographic reconstruction processes, these data are not robust and we cannot directly compare with the QPQ6 results (see the caveat of the interpolation in Section 3.2). The detailed comparison will be conducted with future dense sampling of background sightlines.

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