TYPE Ia SUPERNOVA REMNANT SHELL AT $z = 3.5$ SEEN IN THE THREE SIGHTLINES TOWARD THE GRAVITATIONALLY LENSED QSO B1422+231*

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ABSTRACT

Using the Subaru 8.2 m Telescope with the IRCS Echelle spectrograph, we obtained high-resolution ($R = 10,000$) near-infrared (1.01–1.38 µm) spectra of images A and B of the gravitationally lensed QSO B1422+231 ($z = 3.628$) consisting of four known lensed images. We detected Mg II absorption lines at $z = 3.54$, which show a large variance of column densities ($\sim 0.3$ dex) and velocities ($\sim 10$ km s$^{-1}$) between sightlines A and B with a projected separation of only 8.4$h_{70}^{-1}$ pc at that redshift. This is the smallest spatial structure of the high-$z$ gas clouds ever detected by Rauch et al. found a 20 pc scale structure for the same $z = 3.54$ absorption system using optical spectra of images A and C. The observed systematic variations imply that the system is an expanding shell as originally suggested by Rauch et al. By combining the data for three sightlines, we managed to constrain the radius and expansion velocity of the shell ($\sim 50$–100 pc, 130 km s$^{-1}$), concluding that the shell is truly a supernova remnant (SNR) rather than other types of shell objects, such as a giant H ii region. We also detected strong Fe ii absorption lines for this system, but with much broader Doppler width than that of $\alpha$-element lines. We suggest that this Fe ii absorption line originates in a localized Fe ii-rich gas cloud that is not completely mixed with plowed ambient interstellar gas clouds showing other $\alpha$-element low-ion absorption lines. Along with the Fe richness, we conclude that the SNR is produced by an SN Ia explosion.

Key words: galaxies: abundances – gravitational lensing: strong – intergalactic medium – ISM: supernova remnants – quasars: absorption lines – quasars: individual (B1422+231)

1. INTRODUCTION

Gravitationally lensed QSOs provide us precious opportunities to study spatial structures of high-$z$ gas clouds that intersect the multiple sightlines toward the QSO (e.g., Weymann & Foltz 1983; Foltz et al. 1984; Smette et al. 1995; Rauch et al. 1999, 2001a, 2001b, 2002; Kobayashi et al. 2002; Churchill et al. 2003a; Ellison et al. 2004; Lopez et al. 2005; Monier et al. 2009). By comparing the profiles of absorption lines between multiple sightlines, we can study the density and velocity gradients of intersecting gas clouds directly even at high redshift. Such spatial properties of absorbing gas at high redshift may provide a key to understanding the galaxy formation processes.

The statistical studies of absorption-line systems with the gravitationally lensed QSOs have revealed that the Mg II systems, which trace low-ionization systems, are relatively small (< a few hundred pc) and have clumpy spatial structures (Rauch et al. 2002; Ellison et al. 2004), in contrast to the C iv systems, which are typically a few kpc in size and have fewer structures (Rauch et al. 2001a; Ellison et al. 2004). Studies of single line-of-sight observations and CLOUDY photoionization modeling (Ferland et al. 1998) also suggest that the Fe-rich low-ionization systems should be as small as 10 pc (Rigby et al. 2002; Narayanan et al. 2008). Thus, low-ionization systems appear to have small clumpy spatial structures that directly relate to star-forming activities, such as giant molecular clouds. It is important to investigate their spatial properties with multiple sightlines of gravitationally lensed QSOs, since only the gravitational lens can directly reveal fundamental parameters such as the size and kinematics of gas clouds.

The quadruple gravitationally lensed QSO B1422+231 (Patnaik et al. 1992) is one of the best objects for such a study because of the relatively small separations among multiple sightlines due to the large distance between the lensing galaxy ($z = 0.339$; Kundic et al. 1997; Tonry 1998) and the QSO ($z = 3.628$). This QSO has been observed frequently as one of the most luminous gravitationally lensed high-$z$ QSOs (Bechtold & Yee 1995; Songaila & Cowie 1996; Petry et al. 1998; Rauch et al. 1999, 2001a, 2001b). Rauch et al. (1999, hereafter RSB99) obtained high-resolution optical spectra of images A and C of B1422+231 using Keck HIRES (Vogt et al. 1994) and detected C iv, Si iv, C ii, S ii, and O i absorption lines from the $z = 3.54$ absorption system originally identified by Songaila & Cowie (1996) with strong Ly$\alpha$ and Ly$\beta$ absorption lines. The projected separation between A and C sightlines is only $22.2h_{70}^{-1}$ pc at that redshift. RSB99 suggested that the absorption system is an expanding shell of mass ejection or supernova remnants (SNRs) by analyzing the differences of the absorption profiles of lower-ionization species between images A and C.

In this paper, we report the results of the Subaru near-infrared spectroscopic observations of images A and B of B1422+231. Previous studies of low-ionization gas with Mg II QSO absorption lines were limited to the optical wavelength range and thus to redshifts <2.5, beyond which this transition...
moves into the infrared waveband. Thanks to the advent of highly sensitive near-infrared high-resolution spectroscopy with 8–10 m class telescopes, it is possible now to study this unexplored redshift range. We are conducting a systematic high-resolution spectroscopic survey of high-$z$ Mg II systems with the Subaru IRCS echelle spectrograph. We observed B1422+231 as one of the initial targets and detected Mg II doublet and Fe II absorption lines for the $z = 3.54$ system. Moreover, we succeeded in spatially resolving spectra of images A and B owing to the high spatial resolution in the infrared and the very good seeing of the Subaru Telescope site. This paper is composed as follows: The details of our observations are summarized in Section 2. The data reduction and calibration of spectra are described in Section 3. In Section 4, we show the properties of detected Mg II and Fe II absorption lines. We interpret the properties as signatures of a Type Ia supernova (SN Ia) remnant, which is discussed in Section 5 in detail. Section 6 is the summary of this paper. We adopt a standard cosmology with $\Omega_m = 0.7$, $\Omega_{\Lambda} = 0.3$, $\Omega_k = 0$, and $H_0 = 70 h_{70} = 70$ km s$^{-1}$ Mpc$^{-1}$ throughout this paper and use proper lengths unless otherwise indicated.

2. OBSERVATION

We observed images A and B of B1422+231 (Figure 1) using the Subaru 8.2 m Telescope (Iye et al. 2004) with the IRCS echelle spectrograph (Tokunaga et al. 1998; Kobayashi et al. 2000) in $Y$ (1.01–1.19 $\mu$m) and $J$ (1.16–1.38 $\mu$m) bands. The data were obtained on 2003 February 13 and 2002 April 28 for $Y$ and $J$ bands, respectively. The weather condition for both observing runs was photometric, and the seeing was good ($\sim 0.5''$) during observations for both bands. The integration time per frame was 600 s, and the total integration time was 9000 s and 9600 s for $Y$ and $J$ bands, respectively. The slit widths were 0.60 and 0.30, and corresponding spectral resolutions ($R = \lambda/\Delta \lambda$) were 5000 and 10,000 for $Y$ and $J$ bands, respectively, while the slit length was 3.47 for both observations. Although we used the Subaru Adaptive Optics 36-elements (AO36) system (Takami et al. 2004) for the $Y$-band observation, the improvement of image quality was not good enough that we used the wider slit. The slit position angle (P.A.) was set at P.A. = 39.2$^\circ$ to put both A and B images on the slit simultaneously. The telescope was nodded by 1.5 arcsec along the A–B direction as shown in Figure 2 between alternating frames to offset the sky emission in the subsequent data reduction. We call the frames for positions “a” and “b” as shown in Figure 2. We also observed a standard star, 10 Boo, for flux calibration and removal of telluric absorption lines for both bands. The airmass of the target was distributed in a wide range from 1.0 to 1.5 for both bands, while that of the standard star was about 1.0 and 1.5 for $Y$ and $J$ bands, respectively.

3. DATA ANALYSIS

3.1. Reduction

We used IRAF for data reduction following standard procedures. First, we subtracted “b” frames from corresponding “a” frames to cancel out the dark counts and the sky OH emission lines. All the subtracted frames were combined after the flat-fielding correction and hot/bad pixel correction. Then, we extracted two-dimensional (2D) spectra with the spatial axis along the slit and the dispersion axis perpendicular to the slit for each cross-disperser order using IRAF task “apall” in the “echelle” package. The 2D spectra of each order were combined after applying the wavelength calibration with argon lamp spectra, which were obtained after the observation.

3.2. Deconvolution of A and B Spectra

The lower panel of Figure 2 shows the spatial profile of the 2D spectra of B1422+231 along the slit. The images A and B are almost resolved, but the overlap is not negligible. Image C, which is not a target of this study, is contaminated slightly in the spatial profiles. To obtain precise one-dimensional (1D) spectra of images A and B from the 2D spectra, we fitted the observed spatial profile with the point-spread functions (PSFs) of the three images pixel by pixel in the dispersion axis. This method is similar to that of Lopez et al. (2005), who also observed the multiple images of a gravitational-lensed QSO in a slit simultaneously.

Because the tail of PSF was found to decline slower than that of a Gaussian function, we assumed the following double Gaussians as the form of a PSF:

$$f_i(x, \lambda) = \frac{a_i(\lambda)}{2\sigma^2} \left( \exp\left[ -\frac{(x - b_i)^2}{\sigma^2} \right] + \exp\left[ -\frac{(x + b_i)^2}{\sigma^2} \right] \right),$$

where $i = A, B, C$ are the indices for the lensed images, $x$ is the coordinate of pixels in the spatial axis, $a_i(\lambda)$ is the peak value of each image at wavelength $\lambda$, $b_i$ is the center position of each image, and $\sigma_s$ and $\sigma_d$ are the widths of each Gaussian function ($\sigma_s < \sigma_d$; the subscripts “s” and “d” mean sharp and diffuse, respectively). This function was found to fit the observed profile precisely as shown in the lower panel of Figure 2. The parameters $b_i$, $\sigma_s$, and $\sigma_d$ have to be fixed for linear fitting, which is necessary to converge the fit for observed profiles with low signal-to-noise ratio (S/N). These parameters

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6 IRCS was mounted at the Cassegrain focus at that time. Now it is located at the Nasmyth focus.

7 The AO36 system is now upgraded to AO188 system with much improved image correction capability.

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are successfully determined from the fit of the high-S/N spatial profile made by summing the spatial profiles for 50 pixels along the dispersion axis. The “fit” command of gnuplot was used for the fitting procedure. Though this program is not designed for numerical fitting, it is good enough to conduct the linear fitting. The flux density count at wavelength $\lambda$ for image $i$ was determined by the integral of the PSF $f_i(x, \lambda)$ along the spatial axis, which can be analytically calculated as $\sqrt{\pi a_i(\lambda)(\sigma_i + \sigma_d)}/2$ for double Gaussians. When all the fitting parameters are determined for the entire wavelength range, the final 1D spectrum of each image is constructed by plotting the flux density count along the dispersion axis.

### 3.3. 1D Spectra

Many telluric absorptions of, e.g., water ($H_2O$) and oxygen ($O_2$) plus emission lines of OH appear on the near-infrared spectra for ground-based observations. Although the emission lines are removed by the subtraction of images of alternative pointing (Section 3.1), the absorption lines are still superposed on the extracted spectra of the object. For both bands, we removed the telluric absorption lines by dividing the object spectra by those of an A0 standard star, 10 Boo, which has few intrinsic absorption lines except for two strong hydrogen absorption lines: $Pa\gamma$ ($\sim 10935$ Å) in $Y$ band (order 51 and 52) and $Pa\beta$ ($\sim 12815$ Å) in $J$ band (order 44). Before the division, we removed these hydrogen lines by fitting with a Voigt profile and scaling the telluric absorption lines to correct the airmass difference (Section 2). Figure 3 shows the flux-calibrated spectra of images A and B. We used the continuum of the telluric standard star 10 Boo (5.67 mag in $J$ band from SIMBAD) for flux calibration, assuming an effective temperature of 9480 K.

To avoid the influence of many bumps due to Fe $\Pi$ and Mg $\Pi$ emission lines from the QSO itself on the continuum fitting, the normalized absorption spectra were made by fitting the continuum in a velocity range of $\pm 500$ km s$^{-1}$, which is narrower than the velocity widths of the emission lines ($\sim 1000$ km s$^{-1}$), around the detected absorption lines using the spline3 function.

Heliocentric corrections of $-21.89$ km s$^{-1}$ and $-5.18$ km s$^{-1}$ were applied to $Y$- and $J$-band spectra, respectively. By comparing the detected Mg $\Pi$ absorption lines with C $\Pi$ and Si $\Pi$ absorption lines for image A (RSB99), a residual offset of $-3.4$ km s$^{-1}$ (about a half pixel) was found in our $J$-band spectrum. We shifted the absorption-line spectrum by +3.4 km s$^{-1}$ to match the wavelength of the C $\Pi$/Si $\Pi$ absorption lines with those derived by RSB99 because their spectral resolution ($R = 10,000, \Delta v = 4.4$ km s$^{-1}$) is much better than ours ($R = 10,000, \Delta v = 30$ km s$^{-1}$). This offset is likely to come from the slight change of the instrument setting that occurred between the observation of targets and the acquisition of the argon lamp spectrum. For $Y$-band data, no absorption lines that have obvious peaks as Mg $\Pi$ absorption lines of the $z = 3.54$ system were detected. Therefore, we did not shift the spectra after the heliocentric correction.

### 4. $z = 3.54$ SYSTEM

#### 4.1. Velocity Components

In the final $J$-band spectrum, strong Mg $\Pi$ $\lambda\lambda2796, 2803$ absorption lines with two velocity components at $z = 3.54$ are clearly detected for both images A and B (Figure 3). The corresponding Fe $\Pi$ $\lambda2383$ ($f = 0.320$) and $\lambda2600$ ($f = 0.2394$) absorption lines of this system are also detected in image A (Figure 3), while other Fe $\Pi$ absorption lines, such as $\lambda2344$ ($f = 0.1142$) and $\lambda2587$ ($f = 0.0691$), are not detected probably because of their small oscillator strengths. Hereafter, we will focus only on this $z = 3.54$ Mg $\Pi$ system: the search for other systems and their results will be discussed separately in

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**Figure 2.** Upper panels: the slitviewer $K$-band images obtained during the echelle observation. These are raw images with an integration time of 120 s without corrections for hot/bad pixels. The pixel scale is 0.075 pixel$^{-1}$. The horizontal black thick bar near the center of the images is the shadow of the slit, and four point sources, which are seen in white, are the images A, B, C, and D of B1422+231. The left and right panels correspond to the dither patterns “a” and “b” (see the text for details). The contamination of image C in the slit is slightly seen in this image. Lower panels: the spatial profiles of the spectra along the slit. Points show the observed details). The contamination of image C in the slit is slightly seen in this image. Lower panels: the spatial profiles of the spectra along the slit. Points show the observed details). The contamination of image C in the slit is slightly seen in this image.
Figure 3. Upper panel: the whole Y- and J-band spectra of images A (lower spectra) and B (upper spectra) of B1422+231. The observed spectra were telluric-corrected and smoothed with an 11 pixel (∼3 Å) box car to clearly show the spectra with an effective spectral resolution of R ∼ 4,000. The bumps on the continuum are broad Mg II and Fe II emission lines from the QSO itself at z = 3.628. The vertical bars show the expected positions of absorption lines associated with the z = 3.54 system: solid and dashed lines show the positions of the detected and non-detected lines, respectively. Lower panel: the telluric absorption spectrum in the same wavelength range. This is made by normalizing the spectrum of the standard star, 10 Boo, after removing two hydrogen absorption lines (Pa β and Pa γ) with Voigt profile fitting.

Figure 4. Upper panel: the normalized spectrum of image A around Mg II doublet lines of the z = 3.54 system after the telluric corrections. Lower panel: the normalized spectrum of the standard star 10 Boo, showing the telluric absorption lines. The strong O2 absorption band at around 12690 Å apparently affects the detection and profiles of components 1 and 2 of Mg II λ2796.

S. Kondo et al. (2012, in preparation). Unfortunately, the Mg II λ2796 line is overlapping with the telluric O2 band as shown in Figure 4, and the systematic uncertainty may be left in the profile of Mg II λ2796 even after the removal of the telluric absorption lines (Section 3.3). The impact of the telluric absorption lines will be discussed in the following subsection (Section 4.2) for each velocity component.

This z = 3.54 system was first detected by Songaila & Cowie (1996) as an HI system with N(HI) = 2.3 × 10^{16} cm^{-2} in their high-resolution optical spectrum with Keck HIRES. Later RSB99 detected various metal absorption lines also with Keck HIRES in spatially separated spectra of images A and C. Figure 5 shows the Mg II absorption lines of the z = 3.54 system for both images A and B from our J-band data and C II, Si II, and O I absorption lines of images A and C from RSB99’s optical data. For the Mg II absorption lines, we clearly detected two velocity components for both images A and B at ∼−80 km s^{-1} and ∼+90 km s^{-1}, which are identified as “component 2” and “component 3” in RSB99. The Mg II absorption line that corresponds to “component 1” is also detected at ∼−130 km s^{-1}, but only for image A (Figure 5). The rest-frame equivalent widths (W_r) of detected Mg II λλ2796, 2803 absorption lines are summarized in Table 1. Note that the equivalent widths of lines that are affected by the strong telluric absorption lines are shown with parentheses. The total rest-frame equivalent width of λ2796 for this system is calculated as 0.28 Å. Therefore, this

| Table 1 | Detected Mg II Absorption Lines |
|---------|--------------------------------|
| Image   | Component | W_r(λ2796) (Å) | W_r(λ2803) (Å) | Doublet Ratio |
|---------|-----------|----------------|-----------------|----------------|
| A       | 1         | 0.020          | 0.018          | (1.1)          |
|         | 2         | 0.074          | 0.052          | (1.4)          |
|         | 3         | 0.191          | 0.124          | 1.5            |
| B       | 2         | 0.080          | 0.040          | (1.6)          |
|         | 3         | 0.111          | 0.056          | 2.0            |

Note. W_r of the components that are significantly affected by telluric absorption lines are shown with parentheses.
system is classified as a “weak Mg II system” which is defined as a system with \( W_r(2796) < 0.3 \, \text{Å} \) (Churchill et al. 1999). The corresponding Fe II \( \lambda \lambda 2383, \lambda 2600 \) absorption lines are also detected for component 3 but only for image A as shown in Figure 6 (left panel). The Mg II absorption line is not detected for any component for both images within the uncertainty.

We fit a Voigt profile to the Mg II and Fe II absorption lines and measured the column density, the relative velocity, and the Doppler width using VPFIT\(^9\) (Carswell et al. 1987) and VPGUESS\(^10\) software assuming that each velocity component is composed of just one velocity sub-component, which is a good approximation for estimating column densities from our data with the velocity resolution of \( \Delta v = 30 \, \text{km s}^{-1} \) at most. The results are summarized in Table 2. The shown uncertainty is only that for the VPFIT fitting. For non-detected absorption lines, we calculated the 3\( \sigma \) upper limit of the column density from the S/N of the continuum around the absorption lines. We discuss the characteristics of the detected Mg II and Fe II absorption lines in the following.

### 4.2. Mg II Absorption Lines

Table 1 summarizes the Mg II doublet ratio, which is defined as \( W_r(2796)/W_r(2803) \), for each component of each image. Where both \( \lambda \lambda 2796, 2803 \) absorption lines are not saturated, the doublet ratio should be equal to 2 by simply reflecting the oscillator strengths. For the strongest component (component 3), the doublet ratio is found to be 1.5 for image A, while equal to 2 for image B. Therefore, the absorption line of image A may be slightly saturated while that of image B is not. Although the other weaker components are also unlikely to be saturated in view of the smaller \( W_r(2803) \) than that for component 3 of image B, the doublet ratios for those components show values less than 2. This is probably because \( W_r(2796) \) of components 1 and 2 is underestimated due to the incomplete removal of the heavy telluric absorption lines that are overlapped on those components (Figure 4). Here, we discuss details of the Mg II absorption lines for each component 1, 2, and 3.

**Component 1.** For this component, RSB99 shows that there is no difference between the absorption lines of images A and C, thus the same absorption profile was expected for image B, which is located in between images A and C on the sky. However, we could not detect component 1 in image B despite its existence in the spectrum of image A (Figure 5). In particular, we had expected to detect the Mg II \( \lambda \lambda 2803 \) absorption line because it is not affected by the strong \( \text{O}_2 \) telluric absorption lines, unlike the Mg II \( \lambda 2796 \) absorption line. The Mg II \( \lambda 2803 \) absorption line for component 1 is located right in between two weak telluric absorption lines (Figure 4) and should not be affected by the removal of the telluric absorption lines. Therefore, we conclude that the gas cloud of component 1 covers only images A and C on the sky, suggesting a small-scale sub-structure on this high-redshift cloud.

**Component 2.** Although we tried to fit both Mg II \( \lambda \lambda 2796, 2803 \) lines of component 2 simultaneously, the uncertainties of the three fitting parameters (column density, redshift, and Doppler width) were found to be very large and we could not get any reliable estimate. This is most likely due to the strong telluric \( \text{O}_2 \) band on the Mg II \( \lambda 2796 \) line (Figure 4): systematic uncertainties may be left in the profile of Mg II \( \lambda 2796 \) even after the removal of telluric absorption lines (Section 3.3), which is consistent with the strange doublet ratios for component 2 described above. Therefore, we used only the Mg II \( \lambda 2803 \) line for the Voigt profile fitting for both images A and B for this component. The results are summarized in Table 2. Due to the lack of information on Mg II \( \lambda 2796 \), the uncertainties are fairly large, especially for the Doppler width.

For image A, fortunately, we have information on the Doppler width with a high precision from the high-resolution optical spectrum (RSB99). We tried to estimate the Doppler width of the Mg II \( \lambda 2803 \) line from those of \( \text{C II} \) (9.8 ± 0.5 km s\(^{-1}\)) and Si II (6.7 ± 0.5 km s\(^{-1}\)) lines. Generally, a Doppler width \( b \) consists of thermal ingredient \( b_{th} \) and turbulence ingredient \( b_{tu} \),

\[
\Delta \nu = b^2 = b_{th}^2 + b_{tu}^2, \quad (2)
\]

9. VPGUESS is a graphical interface to VPFIT written by Jochen Liske; see http://www.eso.org/~jliske/vpguess.
10. VPFIT is a Voigt profile fitting package provided by Robert F. Carswell; see http://www.ast.cam.ac.uk/~rfc/vpfit.html.
and the thermal ingredient is expressed as

$$b_{\text{th}} = \frac{2kT}{m},$$

where $k$ is the Boltzmann constant, $T$ is the equilibrium temperature of a gas cloud, and $m$ is the particle mass. From the Doppler widths of two species of different mass (carbon and silicon), the temperature and the turbulence Doppler width were estimated as $T = 65,000 \pm 18,000$ K and $b_{\text{th}} = 2.6 \pm 2.7$ km s$^{-1}$, respectively, resulting in a Doppler width of Mg $\Pi$ of $7.2 \pm 1.3$ km s$^{-1}$. This value is consistent with the Doppler width estimated solely from the Mg $\Pi$ $\lambda$2803 line ($5 \pm 29$ km s$^{-1}$), but with much improved uncertainty.

**Component 3.** Because the influence of the telluric absorption lines is little for component 3 (Figure 4), which is consistent with the doublet ratio of component 3 for image B as discussed above, we fitted a Voigt profile to this component for both Mg $\Pi$ $\lambda\lambda$2796, 2803 lines simultaneously (Table 2). Because the optical absorption profiles are asymmetric for both images

### Table 2

The Results of Voigt Profile Fitting with VPFIT

| Species | Component | $\log N_A$ (cm$^{-2}$) | $\log N_B$ (cm$^{-2}$) | $v_A$ (km s$^{-1}$) | $v_B$ (km s$^{-1}$) | $b_A$ (km s$^{-1}$) | $b_B$ (km s$^{-1}$) |
|---------|-----------|------------------------|------------------------|---------------------|---------------------|---------------------|---------------------|
| Mg $\Pi$ | 1         | 11.9 ± 1.9             | ...                   | −127 ± 16          | ...                 | 2 ± 55              | ...                 |
|         | 2         | 12.4 ± 0.1             | 12.20 ± 0.07          | −78 ± 5            | −85 ± 3             | 7.2 ± 1.3           | 10 ± 9              |
|         | 3         | (12.5 ± 0.4)           | (−77 ± 6)            | 90.6 ± 0.6         | 102.9 ± 0.6         | 9 ± 1               | 7 ± 1               |
| Fe $\Pi$ | 2         | <12.1                  | <12.1                 | ...                 | ...                 | ...                 | ...                 |
|         | 3         | 12.72 ± 0.05           | <12.1                 | 83 ± 3              | ...                 | 23 ± 6              | ...                 |
| Mg I    | 2         | <11.1                  | <11.1                 | ...                 | ...                 | ...                 | ...                 |

**Notes.** The column densities, relative velocities from $z = 3.53850$, and Doppler widths measured with VPFIT are shown for both lines of sight A and B.

* Estimated from the Doppler width of C $\Pi$ and Si $\Pi$. See details in Section 4.1.
A and C (see Figure 5), RSB99 fitted three velocity sub-components to the profile of image A. Because they did not show the fitting results in their paper, we newly fitted the three sub-components to their data11 (Figure 7); the fitting results show the fitting results in their paper, we newly fitted the three velocity sub-components (RSB99), we fitted just one component because the Mg ii absorption profile is convolved with the instrumental function of ∼10 km s\(^{-1}\), which is much larger than the intrinsic width (∼10 km s\(^{-1}\)) of the velocity sub-components. Lower panel: the CII λ1335 absorption profile of component 3 of image A (R ∼ 70,000). The black line shows the observed normalized spectrum from RSB99. The three black dashed lines show the fitted Voigt profiles, while the gray line shows the combined profile.

4.3. Fe ii Absorption Lines

Because iron is essential to assess the chemical abundance of the object, the detection of Fe ii absorption lines for the z = 3.54 system is important to understand the nature of this high-z gas cloud. Note that the detection of Fe ii λ1608 in Keck HIRES spectra is not reported so far because the past optical observations of B1422+231 (Rauch et al. 2001a; Songaila & Cowie 1996) do not cover the wavelength of the shifted Fe ii λ1608 absorption line of the z = 3.54 system (∼7300 Å). In our Subaru IRCS spectra, two Fe ii lines, λλ2383 and 2600, with the largest oscillator strengths were detected, but only for component 3 of image A, which has a higher column density for all the α-elements.

In order to examine the other velocity components of the Fe ii absorption lines for each image A and B, we combined spectra for λλ2344, 2383, and 2600 lines to improve the S/N for Fe ii detection. We did not use λ2587 for this combining because of the intrinsic weakness and the resultant low S/N. First, we transformed the profiles of λλ2344, 2383 lines to that of λ2600 using the following equation:

\[
s'(\lambda) = 1 - \left(1 - s \left(\lambda \times \frac{\lambda_{2600}}{\lambda_{2344} \text{ or } 2383}\right)\right) \frac{f_{2600}}{f_{2344} \text{ or } 2383},
\]

where \(s(\lambda)\) is the observed spectrum, \(s'(\lambda)\) is the transformed spectrum, and \(f\) is the oscillator strength of the lines. Before the combining, the spectrum for Fe ii λ2600 (R = 10,000, Δν = 30 km s\(^{-1}\)) is smoothed to match the spectral resolution to that of λλ2344 and 2383 (R = 5,000, Δν = 60 km s\(^{-1}\)). Finally, each spectrum is combined with weighting by the square of the S/N of the continuum around the absorption lines. The resultant spectra are shown at the top of Figure 6. We also plotted the expected absorption lines with gray lines in Figure 6 assuming log \(N(\text{Mg ii})/N(\text{Fe ii}) = 0.31\), which is the value for component 3 of image A in Table 2 when we assume that the absorption line is composed of a single velocity component. As a result of Voigt profile fitting for these detected Fe ii absorption lines, they are found to have a very large Doppler width (23 ± 6 km s\(^{-1}\); Table 2).

For image A, component 3 is clearly detected again on the combined spectrum, confirming the detection. A weak absorption line is newly noticed between the wavelengths of component 1 and component 2. However, because the center velocity has a large offset from that of the Mg ii line, it is hard to confirm the detection at more than a 3σ level with the present data. Similarly, for image B, two dips near the center velocities of components 1 and 2 are found in the combined spectrum, but the detection is tentative because the expected absorption is much weaker in view of the corresponding weak Mg ii absorption lines.

For component 3 of image B, compared to the expected absorption profile shown with a gray line in the right panel of Figure 6, the observed combined spectrum is almost flat and the absorption appears to be significantly less than the expected amount. The 3σ upper limit is calculated as log \(N = 12.1\) for this non-detected component. From this, the column density ratio Mg ii to Fe ii for component 3 of image B is estimated to be >0.5, which appears to be much larger than that of image A, 0.31. This may suggest a large variance of the column density ratio, log \(N(\text{Mg ii})/N(\text{Fe ii})\), even in a small scale of ∼8 pc, which is the projected separation between sightlines A and B at z = 3.54.

5. DISCUSSION

5.1. Small-scale Structure of Absorbing Gas Cloud at z = 3.54

By comparing the results for images A and B, considerable differences of the column densities of Mg ii absorption lines (log(\(N_A/N_B\)) ∼ 0.20 ± 0.12 dex and 0.37 ± 0.08 dex for component 2 and component 3, respectively) and considerable velocity shears (\(v_A - v_B\) ∼ 7.0 ± 5.8 km s\(^{-1}\) and 12.3 ± 0.8 km s\(^{-1}\) at z = 3.53850 for component 2 and component 3, respectively) are found as shown in Figure 8. Considering the alignment of

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11 The machine-readable data were kindly provided by Dr. Rauch.
three images A, B, and C, the differences were as expected from RSB99’s interpretation of their optical spectra of images A and C in that the relations of the column densities and the relative velocities among three images are \(\log N_A > \log N_B > \log N_C\) (assuming that \(\log N(\text{Mg} \, \text{II})/N(\text{C} \, \text{II})\) is equal for both images B and C) and \(|v_A| < |v_B| < |v_C|\) for both components 2 and 3. The projected distances at \(z = 3.54\) between images are \(d_{AB} = 8.4h_{70}^{-1}\) pc and \(d_{AC} = 22.2h_{70}^{-1}\) pc. This very high spatial resolution (10 pc at \(z = 3.54\) corresponds to \(\sim 1\) mas angular resolution for direct imaging) shows the power of the gravitational lensing (RSB99).

B1422+231 also has a QSO absorption system at slightly higher redshift (\(z = 3.624\)), and the transverse distance reaches 1 pc, which is the smallest separation for QSO absorption systems ever studied with gravitationally lensed QSOs (Bechtold & Yee 1995; Rauch et al. 2001a), though the system shows few variations of absorption lines among multiple images (see Figure 5 of Rauch et al. 2001a) and this system is likely to be associated with the QSO itself. Therefore, the \(\sim 10\) pc structure for the \(z = 3.54\) system is the smallest spatial structure ever detected for QSO absorption systems.

Ellison et al. (2004) observed three lensed images of gravitationally lensed QSO APM 08279+5255 (\(z = 3.911\)) with Hubble Space Telescope (HST). They detected many metal absorption lines at \(1.1 < z < 3.8\), which correspond to the transverse distance, from \(30 h_{70}^{-1}\) pc to \(2.7 h_{70}^{-1}\) kpc. They found large variations of EWs for lower-ionization systems, which are traced with Mg II doublet lines, even on the spatial scale of a few hundred pc, while the higher-ionization systems, which are traced with C IV doublet lines, show less variation of EWs (Rauch et al. 2001a; Ellison et al. 2004). Therefore, low-ionization systems should reflect small-scale gas clouds, which are likely to be related to star formation activities in galaxies. Because this \(z = 3.54\) system’s spatial scale (\(\sim 10\) pc) corresponds to that of the typical Galactic gas clouds, such as giant molecular clouds, H II regions, and SNRs (Rauch et al. 1999), the \(z = 3.54\) system toward B1422+231 is a very precious target that enables the study of such Galactic-scale objects in detail at the galaxy-forming epoch.

5.2. Expanding SNR Shell

5.2.1. Shell Model

The column densities and the velocities of Mg II absorption lines of components 2 and 3 vary among three sightlines as \(\log N_A > \log N_B > \log N_C\) and \(|v_A| < |v_B| < |v_C|\). What types of objects can generate these systematic variances on such a small scale? Based on the nearly symmetric velocity profiles of components 2 and 3 with respect to the systemic velocity that corresponds to \(z = 3.53850\) that are seen in optical spectra of both images A and B (see the profiles for C II and Si II in Figure 5), RSB99 suggested that components 2 and 3 of the \(z = 3.54\) system can be an expanding shell, such as an SNR. When the sightline passes through the center of a gas cloud of the expanding shell, the observed velocity becomes highest because the gas expands along the direction of the sightline, while the column density becomes lowest because the path of the sightline in the shell is shortest at the center. On the other hand, when the sightline passes through the outer edge, the observed velocity becomes lowest, while the column density becomes highest. Applying this model to the \(z = 3.54\) system, RSB99 found that the sightlines of images A and C pass near the outer edge and near the center of an expanding gaseous shell, respectively. The absorption lines of image B, which is newly observed in this study, show intermediate values for both column density and relative velocity; the systematic kinematics seen in this gas cloud support the idea of RSB99 that this \(z = 3.54\) system is truly an expanding shell. Although a contracting (or collapsing) shell is an alternative choice, such an astronomical object is unlikely because the central object of the shell has to pull all the gas symmetrically in a subtle manner: normally such gas should fall through a disk or infalling envelope (not a shell). In fact, no such object is known in the Galaxy and nearby galaxies (see the listed examples of astronomical objects in Section 5.2 in Rauch et al. 2002).

Following RSB99 and Rauch et al. (2002), we will consider a model of a three-dimensional (3D) expanding shell (Figure 9) that has a radius of \(R\) and an expansion velocity of \(v_{\text{exp}}\). Those parameters can be constrained by two kinds of observables: the physical distance between two sightlines at the redshift (e.g., \(d_{AB}\)) and the velocity difference of the two absorption components seen in a single sightline (e.g., \(\Delta v_A\)). In case only two sightlines are available, only the parameters for the expansion “ring” that is on the plane of the two sightlines can be constrained: one is the radius of the ring (\(R \sin \Theta\)), and the other is the expansion velocity of the ring (\(v_{\text{exp}} \sin \Theta\)), where \(\Theta\) is the declination of the ring on the sphere (Figure 10). Although the relation between \(R \sin \Theta\) and \(v_{\text{exp}} \sin \Theta\) can be obtained, the 3D radius (\(R\)) and the expansion velocity (\(v_{\text{exp}}\)) can never be

![Figure 8. Velocity profiles of the z = 3.54 system for images A(Mg II, R = 10,000), B(Mg II, R = 10,000), and C(C II from RSB99, R = 70,000) from bottom to top. The velocity is relative to z = 3.53850. The vertical dashed lines show the peak velocity of components 2 and 3 of image A. The horizontal dashed lines show the normalized continuum level.](image-url)
determined because of the complete lack of information on the absolute location of the ring (Θ) on the sphere: only the possible range of $R \sin \Theta$ and the lower limit of $v_{\exp} \sin \Theta$ can be obtained (RSB99).

On the other hand, in case three independent sightlines (not on a single plane) are available, we can put a strong constraint on the expanding sphere. Since the absolute location of the planes that contain the sightlines cannot be determined in a unique way, $R$ and $v_{\exp}$ still cannot be determined. However, if the $R$ value is fixed, the other parameter $v_{\exp}$ is determined because two $\Theta$ values for the sets of two sightlines (e.g., A/B and B/C) can be determined from the two equations for two rings. Therefore, the relation between $R$ and $v_{\exp}$, which is useful to elucidate the astronomical nature of the shell, can be obtained as a final product (see the detailed description in the appendix of Rauch et al. 2002). In fact, Rauch et al. (2002) suggested that the $z = 0.5656$ absorption system in the three sightlines of gravitationally lensed QSO Q2237+0305 is also an expanding shell because the absorption lines showed variances similar to those of the $z = 3.54$ system. They analyzed the relation between the radius and expansion velocity of the 3D shell and concluded that the expanding shell at $z = 0.5656$ can be interpreted as a supershell or a superbubble of 1–2 kpc size that is frequently observed in the Galaxy and extra-galaxies.

Based on the radial velocities in the two lines of sight (images A and C), RSB99 managed to constrain the parameters in a ring for the $z = 3.54$ system as $9 h_{70}^{-1}$ pc $< R \sin \Theta < 34 h_{70}^{-1}$ pc and $v_{\exp} \sin \Theta > 98$ km s$^{-1}$. Now, with the additional information of image B, we can obtain the relation of $R$ and $v_{\exp}$ of the expanding shell at $z = 3.54$. Note that the model parameters can be completely determined if we have four independent sightlines. Because B1422+231 has four independent gravitationally lensed images, future observations of the fourth image would be very valuable.

We formulated the geometry of the expanding shell as shown in Figure 9 to obtain the radius-velocity relation of the $z = 3.54$ system. The difference of velocities of components 2 and 3 in the sightline of image A, $(\Delta v)_A$, and the distance from the center of the shell to the sightline A, $d_A$, can be expressed as

$$ (\Delta v)_A = 2 v_{\exp} \cos \theta_A $$

$$ d_A = R \sin \theta_A, $$

where $\theta_A$ is the angle from the center of the shell to sightline A (see Figure 9). The equations for images B and C can be given similarly, resulting in six equations in total. Next, we can derive...
two equations about the geometry of triangle ABC:

\[ d_z^2 = d_\delta^2 + AB^2 + 2d_\delta AB \cos \phi \]

\[ d_z^2 = d_\delta^2 + BC^2 + 2d_\delta BC \cos (\angle ABC - \phi), \]

where \( AB \) and \( BC \) are projected distances between images at \( z = 3.54 \), \( \phi \) is the angle between BA and BO, and \( \angle ABC \) is the angle between BA and BC. Now, the parameters \( \Delta v \), \( \Delta v_\delta \), \( \Delta v_C \), \( AB \), \( BC \), \( \angle ABC \) are observed and the nine parameters \( R, v_{\text{exp}}, d_A, d_B, d_C, \theta_A, \theta_B, \theta_C, \phi \) are not determined. If these eight equations are combined, the \( R(v_{\text{exp}}) \) relation can be obtained as a solution.\(^{12}\)

For the \( z = 3.54 \) system, the projected distances are \( AB = 8.4 \, h^{-1} \, \text{pc} \), \( BC = 14.4 \, h^{-1} \, \text{pc} \), and \( AC = 22.2 \, h^{-1} \, \text{pc} \) at \( z = 3.54 \). The angle between AB and BC is 153°. The velocity differences between components 2 and 3 and (\( \Delta v \)) is 168 ± 1 km s\(^{-1}\), (\( \Delta v_\delta \)) = 188 ± 3 km s\(^{-1}\), and (\( \Delta v_C \)) = 197 ± 1 km s\(^{-1}\). By putting those values into the equations, we obtained the function \( R(v_{\text{exp}}) \) that is shown with a solid line in Figure 11 along with two dashed lines that show the 1σ uncertainty range of our calculation: each line corresponds to the cases of (\( \Delta v_\delta \)) = 185 and 191 km s\(^{-1}\). Here, we are only concerned with the uncertainty of (\( \Delta v_\delta \)) because it is the largest among six observables: the available spectrum of image B is only our lower-resolution near-infrared data, while the available spectra of the other two images A and C are higher-resolution optical data of RSB99.

5.2.2. The SNR Origin of the Shell

Figure 11 shows that the radius of the shell is larger than ~20 pc and the expansion velocity is larger than ~120 km s\(^{-1}\). Although there are no a priori constraints, the shortest radius (\( R \leq 30 \) pc) is unlikely requires (1) an exact alignment of the shell with the three sightlines that have similar

\(^{12}\) The analytic solution is given in Equation (A5) in Rauch et al. (2002).
Next, we will discuss the mass of the shell ($M_{\text{tot}}$). RSB99 estimated the number density ($n$) and the size along the line of sight ($L$) for component 3 of image A using the photoionization model as

\[
0.16 \text{ cm}^{-3} \leq n \leq 1.6 \text{ cm}^{-3} \quad (12)
\]

\[
0.015 \text{ pc} \leq L \leq 1.6 \text{ pc}. \quad (13)
\]

From these parameters, RSB99 estimated the mass of a gas cloud ($M_{\text{tot}}$) assuming two geometrical cases: first is a homogeneous cylindrical slab with a thickness $L$ and radius $\pi R$ as a lower limit of the mass; second is a spherical cloud with a radius $\pi R$ as an upper limit of the mass:

\[
0.4 M_\odot \leq M_{\text{tot}} \leq 2700 M_\odot. \quad (14)
\]

Here, we newly obtained an additional constraint on the radius $R$ of the gas cloud as $R \sim 50$–100 pc. Assuming that the gas cloud has a shape of spherical shell with an average radius of $R$, thickness of $L$, and number density of $n$, we can calculate the total mass $M_{\text{tot}}$ of the shell with

\[
M_{\text{tot}} = 4\pi R^2 L n m_{\text{H}_i} \mu, \quad (15)
\]

where $m_{\text{H}_i}$ is the mass of a hydrogen atomic particle ($m_{\text{H}_i} = 1.66 \times 10^{-24} \text{ g}$) and $\mu$ is the reduced mass ($\mu = 4/3$). Here, we ignored the effect of $\cos \theta_i$ on the thickness of the shell (see Figure 9) in view of the large uncertainty of $L$. Using the value range of $n$ and $L$ (Equation 12 and 13) and our result on the radius ($50 < R < 100 \text{ pc}$), $M_{\text{tot}}$ is estimated as

\[
25 M_\odot \leq M_{\text{tot}} \leq 1050 M_\odot. \quad (16)
\]

This is consistent with the original mass estimate by RSB99 (Equation 14) but narrows the mass range by two orders of magnitude.

Because the uncertainty of this estimate is quite large, we try an alternative mass estimate in the following. We will estimate the mass in two ways here, using the column density of H\textsuperscript{i} and Mg\textsuperscript{ii}, in order to check the consistency. In both estimates, we will use the column density of component 3 of image A because the ionization parameter, $U$, of this component was specifically estimated as $\log U = -4.4$ (RSB99), which is low enough that we can estimate the mass simply from the observed column density without any ionization correction. Although the column density of this component may not be the representative value of the shell, we would not expect a large uncertainty of more than an order of magnitude in view of the column density variation among the components seen in images A, B, and C.

First, the H\textsuperscript{i} mass of the shell can be simply calculated as

\[
M_{\text{H}_i} = 4\pi R^2 N_{\text{H}_i} m_{\text{H}_i}, \quad (17)
\]

where $R$ is the size of the shell and $N_{\text{H}_i}$ is the observed H\textsuperscript{i} column density. Using $\log N(\text{H}1) = 16.05 \pm 0.15$ for component 3 of image A (RSB99), the H\textsuperscript{i} mass is calculated as

\[
2.8 M_\odot \leq M_{\text{H}_i} \leq 11 M_\odot. \quad (18)
\]

Because this gas cloud is optically thin, almost all of the hydrogen is likely to be ionized. To estimate the total mass of the shell from the H\textsuperscript{i} mass, we must evaluate the degree of ionization. In Donahue & Shull (1991), the fraction of H\textsuperscript{i} is calculated with

\[
\frac{n(\text{H}1)}{n_H} = (4.6 \times 10^{-6}) U^{-1.026}, \quad -4.7 < \log U < -1.8, \quad (19)
\]

where $n(\text{H}1)$ is the number density of only H\textsuperscript{i} and $n_H$ is the total number density of hydrogen, including H\textsuperscript{ii}. Since the ionization parameter of component 3 of image A is estimated as $\log U = -4.4$ (RSB99), $n(\text{H}1)/n_H$ is calculated as 0.15.

Then, the total hydrogen mass is estimated as

\[
19 M_\odot \leq M_{\text{H}} \leq 75 M_\odot. \quad (20)
\]

Finally, the total mass of the shell can be calculated by multiplying the reduced mass, $\mu$, as

\[
25 M_\odot \leq M_{\text{tot}} \leq 99 M_\odot. \quad (21)
\]

This range is consistent with the typical scrambled gas mass of the observed SNR (10–1000 $M_\odot$), with a radius from about 10 to a few 100 pc (Koo & Heiles 1991).

Next, we attempt one more independent estimate of the total mass of the shell based on the column density of Mg\textsuperscript{ii} instead of H\textsuperscript{i}. The total Mg\textsuperscript{ii} mass in the shell can be estimated using Equation (17), but after replacing H\textsuperscript{i} to Mg\textsuperscript{ii}. For column density $N_{\text{Mg}ii}$, we use the value of component 3 of image A because this component is examined in detail by RSB99. As a result, the total Mg\textsuperscript{ii} mass is calculated as

\[
0.06 M_\odot < M_{\text{Mg}ii} < 0.24 M_\odot \quad (22)
\]

for the assumed range of radius.

The total mass of the shell can be estimated first assuming that all the magnesium is in the form of Mg\textsuperscript{ii}. This assumption is reasonable because the Mg\textsuperscript{i} absorption lines are not detected (the 3$\sigma$ upper limit is calculated as $\log N(\text{Mg}i)[\text{cm}^{-2}] < 11.1$; see Section 4.1 or Table 2). Although the possibility of the existence of a significant amount of Mg\textsuperscript{ii} cannot be dismissed, we ignored the higher ionization states because the ionization parameter $\log U$ of this component is estimated to be quite low as $\log U = -4.4$ (RSB99) based on the photoionization modeling of Donahue & Shull (1991). We assumed the solar abundance, which is suggested by RSB99 for component 3 based on the photoionization modeling by Donahue & Shull (1991). With the solar abundance of magnesium (0.13% in mass; Grevesse et al. 2010), the total mass $M_{\text{tot}}$ is estimated from Equation (22) as

\[
47 M_\odot \leq M_{\text{tot}} < 188 M_\odot. \quad (23)
\]

This mass range is pretty much consistent with the estimate from H\textsuperscript{i} column density, Equation (21).

From the estimated radius and expansion velocity, we can finally constrain the energy of supernova explosion using Equation (11). The remaining parameter in this equation, $n_0$, which is the number density of interstellar medium around the supernova before explosion, can be estimated assuming that the shell consists of all of the gas that existed in the sphere with radius $R$ before explosion, with the following equation:

\[
n_0 = \frac{3 M_{\text{tot}}}{4\pi R^3 m_H \mu}. \quad (24)
\]

With the range of 50 pc $\leq R \leq 100$ pc and $M_{\text{tot}}$ from Equation (23), $n_0$ is calculated as

\[
1.8 \times 10^{-3} \text{ cm}^{-3} < n_0 < 3.6 \times 10^{-3} \text{ cm}^{-3}. \quad (25)
\]

Then, the energy of supernova explosion, $E_0$, is calculated with Equation (11):

\[
3.8 \times 10^{50} \text{ erg} < E_0 < 3.2 \times 10^{50} \text{ erg}. \quad (26)
\]
SNR shell is related to an SN Ia. Iron is localized in the SNR shell. Finally, we conclude that the absorption feature in a more rigorous way to suggest that the $z=3.54$ system (filled circle) is found to be similarly Fe-rich as the three Fe-rich systems (see Figure 12), suggesting solar to sub-solar metallicity.

All those results support the iron richness of the SNR shell at $z=3.54$. The high iron abundance of the SNR naturally suggests that it is an SN Ia. In fact, Rigby et al. (2002) suggested that the three iron-rich systems in their samples have $\alpha/Fe < 0$ and have been enriched by SNe Ia because high iron column density that is similar to magnesium column density cannot be explained by other enrichment processes such as SNe II. Therefore, it is highly likely that the $z=3.54$ system is a gas cloud enriched by SNe Ia. More detailed arguments based on abundance estimates using CLOUDY photoionization modeling will be presented in a separate paper (S. Kondo et al. 2012, in preparation).

If the gas cloud was truly enriched by SN Ia explosion, the total amount of the iron in the gas should be consistent with the yield of the iron from SN Ia explosion. Assuming that the Fe II absorbing gas is in the form of a shell with $R = 50–100$ pc as in Equation (17), the Fe II mass is estimated as $0.07–0.29 \, M_\odot$ from component 3 of image A. Our estimated Fe II mass is consistent with the observed mass of SNe Ia. Scalzo et al. (2010) and Silverman et al. (2011) suggest that the estimated mass of radioactive $^{56}$Ni (eventually decays to $^{56}$Fe) ejected from an SN Ia ranges from 0.02 $M_\odot$ to 1.7 $M_\odot$. Note that the slightly low estimated energy of the SN (Section 5.2.3) also favors an SN Ia interpretation rather than other types of SNe with more energetic explosions. Because our estimate does not include the iron in other ionization states, such as Fe II, within the shell as well as the iron inside the shell, the total mass of iron is expected to be more than the estimated value.

5.3. Type Ia Supernova?

Recall the very broad profile of Fe II absorption lines of component 3 in image A, which is described in Section 4.2. What does this feature mean in the SNR interpretation of the $z=3.54$ system? To answer this question, we first discuss the iron richness of the SNR shell and then examine the broad absorption feature in a more rigorous way to suggest that the iron is localized in the SNR shell. Finally, we conclude that the SNR shell is related to an SN Ia.

5.3.1. Fe Richness

The amount of iron in the gas cloud is crucial to investigate the chemical enrichment by supernovae. Figure 12 shows the distribution of $\log N(\text{Mg})/N(\text{Fe})$ versus $\log N(\text{Mg})$ for weak Mg II systems. The crosses are from Narayanan et al. (2008), who studied 100 weak Mg II systems at $0.4<z<2.4$ using VLT data. The four squares are weak Mg II systems studied with Keck data by Rigby et al. (2002). Note that neither sample includes the systems whose Fe II are not detected. The filled and open squares are confirmed Fe-rich and non-Fe-rich systems based on their photoionization modeling using CLOUDY, respectively. The filled circle shows the $z=3.54$ system ($\log N(\text{Mg})/N(\text{Fe}) = 0.31 \pm 0.07$). The dotted line shows the solar abundance ratio, $\log N(\text{Mg})/N(\text{Fe}) = 0.08$ (Asplund et al. 2005) for the case that all Mg and Fe atoms are in the Mg II and Fe II ionization states. The value of the $z=3.54$ system is found to be closer to the solar value than those for the other weak Mg II systems with similar $N(\text{Mg})$. Narayanan et al. (2008) suggested that any systems near the solar value (dashed line in Figure 12) are truly Fe-rich systems.

Rigby et al. (2002) suggested that their three Fe-rich systems ($N(\text{Fe}) \sim N(\text{Mg})$) have small sizes of $\sim 10$ pc and high metallicity of $>0.1 \, Z_\odot$ (see filled squares in Figure 12). They specifically predicted that the $z=3.54$ system toward B1422+231 should show strong Fe II lines ($N(\text{Fe}) \sim N(\text{Mg})$) in view of the small spatial structure (10 pc) and high metallicity inferred by RSB99. In fact, $\log N(\text{Mg})/N(\text{Fe})$ of the $z=3.54$ system is found to be similarly Fe-rich as the three Fe-rich systems (see Figure 12), suggesting solar to sub-solar metallicity.

5.3.2. Fe Localization

Another characteristic of the Fe II absorption line is the Doppler width (23 ± 6 km s$^{-1}$) that appears to be unusually broad compared with that of $\alpha$-elements (e.g., $b_{\text{FeII}} \sim 9$ km s$^{-1}$). This is quite strange for a QSO absorption system, because the mass of an iron atom is much heavier than that of $\alpha$-elements, thus the width of an Fe II absorption line should be smaller than that of $\alpha$-elements. We first compared the widths of Mg II and Fe II lines of the $z=3.54$ system with the past surveys of weak Mg II systems (Rigby et al. 2002; Churchill et al. 2003b; Narayanan et al. 2008). Figure 13 shows correlation of the Doppler widths of Mg II and Fe II lines of weak

![Figure 12. $N(\text{Mg})$ vs. $N(\text{Fe})$ of weak Mg II systems. The crosses are from Narayanan et al. (2008), the squares are from Rigby et al. (2002), and a filled circle shows component 3 of image A of the $z=3.54$ system. The filled squares show confirmed Fe-rich systems, while an open square shows the confirmed non-Fe-rich system (Rigby et al. 2002). The dotted line shows the solar abundance ratio (Asplund et al. 2005). The $z=3.54$ system (filled circle) is located in a horizontal branch near the solar value, where the confirmed Fe-rich systems (filled squares) are distributed.](image-url)
the observed data for both Fe\textsuperscript{II} there are no obviously corresponding α lines, this iron gas cloud is inferred to be localized in the shell. The localization of iron in the SNR also supports the SN Ia origin of the SNR shell: the Fe\textsuperscript{II} absorption lines on the Fe\textsuperscript{II} ii system (component 3 of image A). The dotted line shows the location where the widths of Mg\textsuperscript{II} and Fe\textsuperscript{II} are identical. While the crosses are distributed along or below the dotted line, the point of the z = 3.54 system is located above the line with a large offset.

Mg\textsuperscript{II} systems. The points should be located below the dotted line (b\textsubscript{MgII} = b\textsubscript{FeII}) because iron is heavier than magnesium. In fact, most data points from the literature are distributed along or below the dotted line. However, the z = 3.54 system is found to be located significantly above the line even considering the uncertainty, suggesting the uniqueness of this system.

We first checked the possibility of blending of other absorption lines on the Fe\textsuperscript{II} absorption lines. For example, if Mg\textsuperscript{II} absorption systems existed at z = 3.22 and z = 2.87, strong metal absorption lines Mg\textsuperscript{II} λ\textsubscript{2796}, 2803 would blend with the Fe\textsuperscript{II} λ\textsubscript{2600} (λ = 11804 Å) and λ\textsubscript{2583} (λ = 10814 Å) lines, respectively. However, such absorption systems have not been reported in Songaila & Cowie (1996) and Rauch et al. (2001a), who detected many Lyman series lines and C\textsuperscript{IV} absorption lines of B1422+231. Therefore, we conclude that the broad features of Fe\textsuperscript{II} lines are real.

Here we try to evaluate the excess Fe\textsuperscript{II} absorption by decoupling the broad feature into two sub-components. If we compare the Mg\textsuperscript{II} and Fe\textsuperscript{II} profiles, the excess exists on the blue side of the Mg\textsuperscript{II} absorption peak (Figure 6). Then, we fitted two velocity components to both Fe\textsuperscript{II} λ\textsubscript{2600} and 2383 lines with the fixed Doppler widths of 9 km s\textsuperscript{-1}, which is the upper limit estimated from the Doppler width of Mg\textsuperscript{II} (~9 km s\textsuperscript{-1}). The results are shown in the bottom panel of Figure 14. The black line shows the component whose redshift is fixed to the value of the Mg\textsuperscript{II} absorption line during the fitting, while the gray line shows the other excess component, for which the redshift was not fixed. The resultant difference of peak velocity between the two velocity components is 26 ± 7 km s\textsuperscript{-1}, and the column densities of blue and red components are log N [cm\textsuperscript{-2}] = 12.3 ± 0.2 and 12.5 ± 0.1, respectively. This fitting appears to match well with the observed data for both Fe\textsuperscript{II} λ\textsubscript{2600} and 2383 lines.

Now, the question is, what is the blue component? Because there are no obviously corresponding α-element absorption lines, this iron gas cloud is inferred to be localized in the shell. The localization of iron in the SNR also supports the SN Ia origin of the SNR shell: the Fe\textsuperscript{II} features imply the ejection of the mass from the SN Ia, while the other α-element absorption lines are likely to be the interstellar gas scrambled by the shock of the SNR. In our Galaxy, Hamilton et al. (1997) observed SN 1006, which is an SN Ia remnant, with absorption lines on a spectrum of the Schweizer–Middleditch star, whose sightline intersects near the center of SN1006. Despite the age difference (~1000 yr for SN 1006, ~10\textsuperscript{5} yr for the z = 3.54 system), it would be useful to compare those two objects in detail to infer the nature of the z = 3.54 SNR shell because the geometrical configuration is very similar. For SN 1006, a very broad (~5,000 km s\textsuperscript{-1}) Fe\textsuperscript{II} absorption line is detected at the systemic velocity, while the ejected Si\textsuperscript{II} shows a redshift of ~5,000 km s\textsuperscript{-1}. This suggests that the mixing of ejected iron with interstellar gas occurs after the mixing of ejected α-elements. The two velocity sub-components of Fe\textsuperscript{II} absorption lines of component 3 of image A can be interpreted as meaning that the red component with the same velocity as the α-element lines comes from Fe gas that mixed with the scrambled interstellar gas, and the blue component comes from Fe gas that has not been mixed with it yet (Figure 15). Therefore, we might witness the mixing process of ejected iron with interstellar gas at z = 3.54.
5.3.3. SNe Ia at High Redshift

In this section, we saw evidence of the richness and localization of iron in the SNR shell at $z = 3.54$. The detected iron richness cannot be explained by processes other than SNe Ia. Moreover, the suggested localization of iron in the shell supports the SN Ia interpretation. From these facts, we conclude that the $z = 3.54$ system is an SN Ia remnant.

The extragalactic SN Ia has been studied extensively for the supernova cosmology (Goobar & Leibundgut 2011). However, even the most distant SN Ia event ever detected is at $z = 1.55$ (Rodney et al. 2012), and more distant objects that are important for the study of cosmic chemical enrichment history are hard to detect with 8–10 m class telescopes. For studying such high-$z$ SNe Ia, absorption systems toward gravitational-lensed QSOs may serve as good targets as is the case for this $z = 3.54$ system toward B1422+231. Even for the single sightline, the Fe-rich absorption systems as seen in Figure 12 would become good targets for studying chemical enrichment history at high redshift ($z > 2$) with more data available with sensitive high-resolution spectroscopy with adaptive optics (see Kobayashi et al. 2005).

6. SUMMARY

We obtained near-infrared high-resolution ($R = 10,000$) spectra of images A and B of gravitationally lensed QSO B1422+231 with the Subaru 8.2 m telescope and the IRCS echelle spectrograph. Although the observed PSFs of images A and B are partially overlapping in the slit, we managed to extract spectra for each image A and B to examine the differences of absorption lines. We detected Mg II $\lambda\lambda2796, 2803$ absorption lines of the $z = 3.54$ system, which had been found in images A and C in optical spectra by RSB99. Corresponding Fe II $\lambda\lambda2383$, 2600 absorption lines are also detected, but only for component 3 of image A. The projected separation between A and B images at $z = 3.54$ is just $8.4 h_70^{-1}$ pc, and we found considerable differences of column density ($\Delta\log N \sim 0.3$ dex) and velocity shear ($\Delta v \sim 10$ km s$^{-1}$) between both images on such a small scale. These differences suggest the smallest structure of gas clouds ever detected for QSO absorption systems.

Considering the physical origin of the differences of $\alpha$-element absorption lines among three images A, B, and C, we conclude that the $z = 3.54$ system is an expanding shell as originally suggested by RSB99. The information of three images enables us to analyze the 3D structure of the absorbing gas cloud and conclude that this $z = 3.54$ system is an SNR shell whose radius and expansion velocity are $50–100$ pc and $\sim 130$ km s$^{-1}$, respectively. We estimated several physical parameters of the shell, which are found to be consistent with SNRs: the age is $\sim 10^5$ yr, the mass of the shell is $\sim 100$ $M_\odot$, and the energy of the SNe is $\sim 10^{50}$ erg.

We also found that the Fe II absorption lines of the $z = 3.54$ system have much larger column density and Doppler width than those of the weak Mg II systems in the literature. The small column density ratio $N$(Mg II)/$N$(Fe II) ($=0.31 \pm 0.07$) is indicative of the richness of the iron of the $z = 3.54$ system. We also estimated the mass of Fe II as $0.07–0.29$ $M_\odot$, which is roughly consistent with the yield of observed SNe Ia. Moreover, the large Doppler width of Fe II, which is interpreted as the existence of one more velocity component that is blueshifted and extremely Fe-rich, suggests that the Fe-rich gas cloud is localized in the expanding shell of an SNR. From these results, we conclude that the SNR shell at $z = 3.54$ is produced by an SN Ia explosion.

Supernova explosions are thought to be one of the most important processes that drive the formation of galaxies through the dynamical energy input and chemical enrichment. If this $z = 3.54$ system is truly an SNR, it is the farthest sample of a supernova ever observed. If higher-S/N and/or higher spectral resolution data of B1422+231 were obtained in the future, the difference between iron and $\alpha$-elements would be more clearly confirmed. Then, physics of the mixing of interstellar gas with ejected gas from supernovae could be discussed in detail. If the spectrum of image D is also obtained, the radius and expansion velocity can be strictly determined with the expanding shell model.

This $z = 3.54$ system illustrates the power of the gravitational lensing effect for the study of QSO absorption systems with extremely high spatial resolution and multiple sightlines. In the case of the present study, the separation between images A and B is only $<10$ pc at $z = 3.5$, which corresponds to about 1 mas angular resolution. More observations of gravitationally lensed QSOs will reveal the kinematics (e.g., expansion) of gas clouds on interstellar scales at high redshift during crucial phases of galaxy formation.

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REFERENCES

Arnal, E. M., & Corti, M. 2007, A&A, 476, 255
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336, Cosmic Abundances as Records of Stell lar Evolution and Nucleosynthesis, ed. T. G. Barnes, III & F. N. Bash (San Francisco, CA: ASP), 25
Bechtold, J., & Yee, H. K. C. 1995, AJ, 110, 1984
Capp, C., Niemela, V. S., Amorín, R., & Vasquez, J. 2008, A&A, 477, 173
Carswell, R. F., Ibh J. K., Baldwin, J. A., & Arwood, B. 1987, ApJ, 319, 709
Churchill, C. W., Mellon, R. R., Charlton, J. C., & Vogt, S. S. 2003a, ApJ, 593, 203
Churchill, C. W., Rigby, J. R., Charlton, J. C., & Vogt, S. S. 1999, ApJS, 120, 51
Churchill, W. C., Vogt, S. S., & Charlton, C. J. 2003b, AJ, 125, 98
Cichowolski, S., Romero, G. A., Ortega, M. E., Cappa, C. E., & Vasquez, J. 2008. Boletín de la Asociación Argentina de Astronomía La Plata Argentina, 51, 185
Daigle, A., Joncas, G., & Parizeau, M. 2007, ApJL, 661, 285
Donahue, M., & Shull, J. M. 1991, ApJ, 383, 511
Draine, B. T. 2011, Physics of the Interstellar and Intergalactic Medium (Princeton, NJ: Princeton Univ. Press)
Ellison, S. L., Buta, R., Pettini, M., et al. 2004, A&A, 441, 79
Erland, G. J., Korista, K. T., Verner, D. A., et al. 1998, PASP, 110, 761
Foltz, C. B., Weymann, R. J., Roper, H. J., & Chaffee, F. H., Jr. 1984, ApJ, 281, L1
Grevesse, N., Asplund, M., Sauval, A. J., & Scott, P. 2010, ApSS, 328, 179
Goobar, A., & Leibundgut, B. 2011, Ann. Rev. Nucl. Part. Sci., 61, 251
Hamilton, A. J. S., Fesen, R. A., Wu, C.-C., Crenshaw, D. M., & Sarazin, C. L. 1997, ApJ, 481, 838
Iye, M., Karoji, H., Ando, H., et al. 2004, PASJ, 56, 381
Kobayashi, N., Terada, H., Goto, M., & Tokunaga, A. 2002, ApJ, 569, 676
Kobayashi, N., Tokunaga, A. T., Terada, H., et al. 2000, Proc. SPIE, 4008, 1056
Kobayashi, N., Tsujimoto, T., & Minowa, Y. 2005, in Science with Adaptive Optics, ed. W. Brandner & M. E. Kasper (Berlin: Springer), 352
Koo, B.-C., & Heiles, C. 1991, Apl, 382, 204
Kothes, R., & Kerton, C. R. 2002, A&A, 390, 337
Kundic, T., Hogg, D. W., Blandford, R. D., et al. 1997, AJ, 114, 2276
Lopez, S., Reimers, D., Gregg, M. D., et al. 2005, ApJ, 626, 767
Monier, E. M., Turnerhe, D. A., & Rao, S. 2009, MNRAS, 397, 943
Morton, D. C. 1991, ApJS, 77, 119
Narayanan, A., Charlton, J. C., Misawa, T., Green, R. E., & Kim, T.-S. 2008, ApJ, 689, 782
Patnaik, A. R., Browne, I. W. A., Walsh, D., Chaffee, F. H., & Foltz, C. B. 1992, MNRAS, 259, 1P
Petry, C. E., Impey, C. D., & Foltz, C. B. 1998, ApJ, 494, 60
Rauch, M., Sargent, W. L. W., & Barlow, T. A. 1999, ApJ, 515, 500
Rauch, M., Sargent, W. L. W., & Barlow, T. A. 2001, ApJ, 554, 823
Rauch, M., Sargent, W. L. W., Barlow, T. A., & Carswell, R. F. 2001, ApJ, 562, 76
Rauch, M., Sargent, W. L. W., Barlow, T. A., & Simcoe, R. A. 2002, ApJ, 576, 45
Rigby, J. R., Charlton, J. C., & Churchill, C. W. 2002, ApJ, 565, 743
Rodney, S. A., Riess, A. G., Dahlen, T., et al. 2012, ApJ, 746, 5
Scalzo, R. A., Aldering, G., Antilogus, P., et al. 2010, ApJ, 713, 1073
Shields, G. A. 1990, ARA&A, 28, 525
Silverman, J. M., Ganeshalingam, M., Li, W., et al. 2011, MNRAS, 410, 585
Smirke, A., Robertson, J. G., Shaver, P. A., et al. 1995, A&AS, 113, 199
Songaila, A., & Cowie, L. L. 1996, AJ, 112, 335
Takami, H., Takato, N., Hayano, Y., et al. 2004, PASJ, 56, 225
Tielens, A. G. G. M. 2005, The Physics and Chemistry of the Interstellar Medium (Cambridge: Cambridge Univ. Press)
Tokunaga, A. T., Kobayashi, N., Bell, J., et al. 1998, Proc. SPIE, 3354, 512
Tonry, J. L. 1998, AJ, 115, 1
Vogt, S. S., Allen, S. L., Bigelow, B. C., et al. 1994, Proc. SPIE, 2198, 362
Weymann, R. J., & Foltz, C. B. 1983, ApJ, 272, L1