CONSTRAINING STELLAR PROPERTIES OF INTERVENING DAMPED Ly$\alpha$ AND Mg$\equiv$ ABSORBING GALAXIES TOWARD GRB 050730

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ABSTRACT

We performed multiband deep imaging of the field around GRB 050730 to identify the host galaxies of intervening absorbers, which consist of a damped Ly$\alpha$ absorption (DLA) system at $z_{abs} = 3.564$, a sub-DLA system at $z_{abs} = 3.022$, and strong Mg$\equiv$ absorption systems at $z_{abs} = 1.773$ and 2.253. Our observations were performed after the gamma-ray burst afterglow had disappeared. Thus, our imaging survey has a higher sensitivity to the host galaxies of the intervening absorbers than the normal imaging surveys in the direction of QSOs, for which the QSO glare tends to hide the foreground galaxies. In this deep imaging survey, we could not detect any unambiguous candidates for the host galaxies of the intervening absorbers. Using the 3$\sigma$ upper limit of the flux in the optical to mid-infrared observing bands, which corresponds to the UV to optical bands in the rest frame of the intervening absorbers, we constrained the star formation rates and stellar masses of the hosts. We estimated the star formation rates for the intervening absorbers to be $\lesssim 2.5 M_\odot$ yr$^{-1}$ for $z > 3$ DLAs and $\lesssim 1.0 M_\odot$ yr$^{-1}$ for $z \sim 2$ Mg$\equiv$ systems. Their stellar masses are estimated to be several times $10^9 M_\odot$ or smaller for all intervening galaxies. These properties are comparable to dwarf galaxies, rather than the massive star-forming galaxies commonly seen in the $z > 2$ galaxy surveys based on emission-line selection or color selection.

Key words: galaxies: evolution – galaxies: ISM – galaxies: stellar content – gamma-ray burst: individual (GRB 050730)

Online-only material: color figures

1. INTRODUCTION

Exchange of gas and metals between the intergalactic medium and galaxies is a fundamental process of galaxy formation and evolution. In the standard model of galaxy formation based on the cold dark matter (CDM) cosmology (e.g., White & Rees 1978; Fall & Efstathiou 1980), galaxies are thought to be formed by star formation caused by the cooling and condensation of gas in the core of galactic halos produced by the hierarchical clustering of dark matter. To reveal the process of galaxy formation and evolution, it is important to explore the gaseous and stellar properties of young galaxies at high redshifts. The study of stellar populations in high-redshift ($z > 2$) galaxies has been largely developed by the detection of color-selected galaxies, such as Lyman break galaxies (LBGs; Steidel et al. 2003), or emission-line selected galaxies, such as Ly$\alpha$ emitters (LAEs; Cowie & Hu 1998). The study of these galaxy populations provides us with the properties of their stellar population, including star formation rate (SFR), stellar mass, and age. The gaseous properties of high-redshift galaxies, such as hydrogen and metal abundances, have also been studied in this decade, but these studies are mostly based on observations of intergalactic matter identified as hydrogen or metal absorption lines in the spectra of bright QSOs. It is difficult to connect the stellar properties of the emission-line selected galaxies to the gaseous properties of the absorption-line selected galaxies, as they have very different selection biases. The emission-selected samples are biased by their flux and depend on the depth of the imaging surveys. Therefore, they only provide information in galaxies at the brightest end of the luminosity function. In contrast, the absorption-selected samples are selected homogeneously by their gas content, and thus, they are less biased by the flux of the host galaxies. To connect stellar and gaseous properties of high-redshift galaxies, it is essential to detect the emission from the galaxies associated with the high-redshift absorption line systems.

Among the several absorption lines seen in the spectra of background QSOs, the damped Ly$\alpha$ absorption (DLA) systems (Wolfe et al. 1986) present unique opportunities to select H$\equiv$-rich (H$\equiv$ column density ($N_{H\equiv}$) $\gtrsim 10^{20.5}$ cm$^{-2}$) galaxies at high redshift. The DLAs dominate the H$\equiv$ content of the universe at $z > 2$ (e.g., Péroux et al. 2003; Prochaska & Wolfe 2009; Noterdaeme et al. 2009) and contain a large amount of H$\equiv$ gas mass, accounting for a large fraction of the present-day stellar mass (Cole et al. 2001). Thus, the high-$z$ galaxies associated with absorbers such as DLAs are expected to be progenitors of present-day galaxies. Many attempts to identify DLA host galaxies have been made so far. At low redshift ($z \lesssim 1$), a few dozen DLA absorbing galaxies have been established (e.g., Rao et al. 2003, 2011; Chen & Lanzetta 2003), although more than 50% of the known low-redshift DLAs remain unidentified. At high redshift ($z \gtrsim 1$), however, the success rate for discovering DLA host galaxies is quite low, especially at $z > 2$. Only a few DLA host galaxies have been identified (e.g., Möller et al. 2002, 2004; Péroux et al. 2012). This low discovery rate could be caused by the fact that most DLA host galaxies are faint and compact. The glare of the background QSOs also severely hampers the detection of the faint stellar emission from the DLAs. Some independent theoretical predictions suggest that DLA host galaxies have typical luminosities of sub-$L^*$ with a typical proper size of $\sim 3$ kpc, and 60%–90% of them could be hidden by the glare of bright QSOs (e.g., Fynbo et al. 1999; Okoshi & Nagashima 2005). The limited sample size of identified galaxies associated with DLAs prevents us from...
In this paper, we present the results of optical to near-infrared deep imaging observations of the field around GRB 050730. The layout of the paper is as follows: the optical and near-infrared observations and data analysis are presented in Section 2. In Section 3, we provide the results of our spectral energy distribution (SED) fitting analysis and discuss the properties of the intervening absorbers toward GRB 050730. Our main results are summarized in Section 4. In this paper, we adopt an ΛCDM cosmology with \( \Omega_\Lambda = 0.7, \Omega_M = 0.3, \) and \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}. \)

2. OBSERVATIONS AND RESULTS

2.1. Optical and Near-infrared Imaging

We observed the field around GRB 050730 in 2007 May and June using the Multi-Object InfraRed Camera and Spectrograph (MIORCS; Suzuki et al. 2008) mounted on the Cassegrain focus of the Subaru telescope at Mauna Kea, Hawaii. We took images in the J and K_s bands, with total exposure times of 3600 and 11,160 s, respectively. Seeing sizes were roughly 0.5'5 in the J band and 0.58' in the K_s band. A standard star (FS136; Leggett et al. 2006) was observed for flux calibration at the beginning or end of each observation. The data were reduced using a purpose-built pipeline software package called MCSRED (Tanaka et al. 2011).

First, we performed flat fielding with self-flat frames, and then we subtracted the sky background from each image. Finally, the data were co-registered and combined.

We also obtained B-, R-, and z'-band optical images of the GRB 050730 field using SuprimeCam (Miyazaki et al. 2002) mounted at the prime focus of the Subaru telescope. The total exposure times for the B, R, and z' bands were 1950, 4000, and 2530 s, respectively. The seeing size varied between 1'2 and 1'5 throughout the night of the observations. The data were reduced with standard procedures (i.e., dark and bias subtraction, flat fielding and sky subtraction, distortion correction, point-spread function (PSF) matching, and mosaicking) using the SDFRED package (Yagi et al. 2002; Ouchi et al. 2004). The images were calibrated with observations of the SA104 standard stars (Landolt 2009) at an airmass similar to the observations of the GRB 050730 field.

2.2. Optical and Mid-infrared Archived Images

The field around GRB 050730 was imaged with several telescopes to detect its optical afterglow just after the burst (e.g., Pandey et al. 2006). Moreover, subsequent follow-up deep imaging surveys to detect its host galaxy were made more than several months after the burst when the optical afterglow has disappeared (Chen et al. 2009). We used the archived images to specify the position of the afterglow of GRB 050730 and to provide additional leverage to identify the candidate of the galaxy associated with intervening absorbers.

We used the R-band snapshot images of the field around GRB 050730 observed on 2007 July 30 (just after the burst), with Very Large Telescope (VLT)/FORS2, obtained from the ESO archive. We also used the VLT/FORS2 R- and I-band deep imaging data observed in 2008 February–May (more than six months after the burst; i.e., no afterglow in the image). The total exposure times of the deep imaging data are 9800 and 600 s in the R and I bands, respectively. A basic calibration including bias subtraction, flat fielding, and sky subtraction was performed on each image using the EsoRex FORS pipeline. The resultant
images have seeing sizes of 0′′7 and 1′0 in the R and I bands, respectively.

We also obtained the $L_*$-band (3.6 $\mu$m) Spitzer/IRAC images of the field of GRB 050730 from the Spitzer archive (Laskar et al. 2011). The total exposure time was 6970 s. The data were reduced using the standard Spitzer Science Center pipeline software, whose outputs are Basic Calibrated Data (BCD) FITS files for each frame. The image mosaics were created from the BCD data using the MOPEX software. The FWHM of the PSF in the final image is estimated to be around 1′′9.

### 2.3. Limiting Magnitude

To estimate the limiting magnitude, we derived the 1σ background fluctuation in each band by directly measuring the sky fluxes within $2 \times \text{FWHM}$ apertures randomly placed on the images. Table 1 summarizes the 3σ limiting magnitude within a $2 \times \text{FWHM}$ diameter aperture and seeing size in each band, as well as the observational information. The limiting magnitudes listed in this table are corrected for Galactic extinction toward the field of GRB 050730 ($A_V = 0.156$; Schlegel et al. 1998). Hereafter, we used the magnitude corrected for Galactic extinction.

The $R$-band image of VLT/FORS2 is the deepest among the obtained images. The limiting magnitude of the $R$-band image is 27.69 (AB), which is more than 1 mag deeper than the rest. Therefore, we use the $R$-band image for detecting galaxies around GRB 050730. However, we do not use the $R$-band image for deriving the luminosity because the $R$ band corresponds to the rest-frame UV wavelength at the absorbers’ redshift ($z > 1$), and thus mainly traces the star formation activities in galaxies rather than the stellar properties. The $K_s$ band corresponds to the rest-frame optical band at the absorbers’ redshift ($B$ for $z_{abs} = 3.969$ and 3.564, $V$ for $z_{abs} = 3.022$, $R$ for $z_{abs} = 2.253$, and $I$ for $z_{abs} = 1.773$), and thus traces the long-lived stellar population in the galaxies. Therefore, we used the $K_s$-band image to obtain the galaxy luminosity or its upper limit. Note that although the $L$ (3.6 $\mu$m)-band image also traces the rest-frame optical wavelength at the absorbers’ redshift, its $L_*$ magnitude is drawn from a luminosity function at $z < 2$ from Ilbert et al. (2005).

#### Table 1

| Band | Instrument | Date | Exp. Time (s) | Seeing (′) | Limiting Magnitude$^a$ |
|------|------------|------|---------------|------------|------------------------|
| B    | SuprimeCam | 2007 Jun 13 | 1950 | 1.6 | 26.21 |
| V    | FOCAS      | 2010 May 5 | 180  | 0.8 | 25.73 |
| $R_s$| SuprimeCam | 2007 Jun 13 | 4150 | 1.5 | 26.48 |
| $z$  | SuprimeCam | 2007 Jun 13 | 2530 | 1.5 | 25.10 |
| J    | MOIRCS     | 2007 Jun 8 | 3600 | 0.5 | 25.22 |
| $K_s$| MOIRCS     | 2007 May 1  | 11160| 0.6 | 25.04 |

### Imaging data from archive

- $R_{sp}$: FORS2/VLT 2006 Feb–May 9800 0.7 27.69
- $I$: FORS2/VLT 2006 Feb 25 600 1.0 24.96
- $L$ (3.6 $\mu$m): IRAC/Spitzer 2008 Mar 11 6970 1.9 24.65

### Subaru spectroscopy

- 300B + SY47: FOCAS 2010 May 5 5400 0.7 ...

#### Notes.

$^a$ All magnitudes are shown as 3σ limiting magnitudes measured in 2 $\times$ FWHM apertures. The data were corrected for Galactic extinction (Schlegel et al. 1998).

#### Table 2

List of the Intervening Absorbers Toward GRB 050730

| Type | Redshift | log(N(H i)) (cm$^{-2}$) | Mg ii $W_{5170}^b$ (Å) | [Si/II] | $M_{AB}$ | $L/L_*$ $^a$ | SFR ($\text{M}_\odot\text{yr}^{-1}$) | log($M_{\text{stellar}}/M_\odot$) |
|------|----------|------------------------|-----------------------|---------|---------|-------------|------------------|------------------------|
| DLA  | 3.564    | 20.03 ± 0.10           | ...                   | <-1.3   | >=-20.79 (B) | <0.22       | <1.62, 2.45        | <9.52, <9.92 |
| Sub-DLA | 3.022   | 19.90 ± 0.10           | ...                   | -1.5 ± 0.2 | >=-20.49 (V) | <0.12       | <1.24, 1.87        | <9.68, <9.92 |
| Mg ii | 2.253    | ...                    | 0.886 ± 0.031         | ...     | >=-19.95 (R) | <0.08       | <0.75, 1.14        | <9.66, <9.68 |
| Mg ii | 1.773    | ...                    | 0.943 ± 0.023         | ...     | >=-19.49 (I) | <0.03       | <0.49, 0.74        | <9.71, <9.54 |

#### Notes.

$^a$ The 3σ upper limit in the $K_s$-band image (Table 1), which corresponds to the rest-frame optical at the redshift of the absorbers ($B$ for $z = 3.564$, $V$ for $z = 3.022$, $R$ for $z = 2.253$, and $I$ for $z = 1.773$), was used for calculating the upper limit of $L_*/L_*$. The $L_*$ magnitudes for the $B$, $V$, and $R$ bands are drawn from a luminosity function at $2 < z < 3.5$ from Marchesini et al. (2007), and the $L_*$ magnitude for the $I$ band is drawn from a luminosity function at $z < 2$ from Ilbert et al. (2005).

$^b$ The case where no counterpart associated with the absorbers is detected in the deepest $R$-band image ($R > 27.14$).

$^c$ The case where the candidate G1 ($R \sim 26.69$) is associated with the absorber at each redshift.
for $z_{\text{abs}} = 1.773$. We emphasize that the limiting magnitude for our $K_s$-band image corresponds to a luminosity less than $0.3 L_\odot$ at any absorber’s redshift, and we note that we can reach the sensitivity necessary to detect sub-$L_\odot$ galaxies, which are expected to be major contributors to the DLA cross section (Okoshi & Nagashima 2005).

2.4. Sources around GRB 050730

Figure 1 shows the acquired images of the field around the GRB 050730 afterglow. The size of each panel is $25'' \times 25''$, which roughly covers the area around $\sim 100$ kpc from the line of sight toward the GRB afterglow at the absorbers’ redshift ($z_{\text{abs}} \sim 1.7-3.9$). We detected 27 galaxies within this field of view in the deepest $K_s$-band image. Only 7 out of the 27 galaxies are detected in the $K_s$ band.

Long-duration GRBs are known to occur exclusively within a few kiloparsecs of the center of star-forming galaxies (Bloom et al. 2002; Fruchter et al. 2006). We confirmed that there was no discernible flux associated with the intrinsic GRB–DLA absorbers at $z \sim 3.968$ within 10 kpc around the afterglow, as already reported in Chen et al. (2009), although our limiting magnitude in the $R$ band ($\sim 27.4$) is 1 mag deeper than that of Chen et al. (2009, $R_c \sim 26.4$).

By contrast, intervening DLA or Mg $\text{II}$ absorbers are selected independently of any emission or stellar population. Their sight lines are selected by a cross section of the intervening galaxies and should preferentially intersect the outer regions of the interstellar medium in the galaxies. To identify possible candidates for the galaxies associated with the intervening absorbers, we first eliminate galaxies that are located too far away from the line of sight toward the GRB afterglow to produce the observed DLA or Mg $\text{II}$ absorptions. We adopted a scaling relation between the galaxy’s luminosity ($L$) and halo radius ($R$) in the form

$$\frac{R}{R_\odot} = \left( \frac{L}{L_\odot} \right)^t$$

(1)

to constrain the extension of the gas cloud associated with the DLA or Mg $\text{II}$ host galaxies following the method described in Fynbo et al. (1999). In this formula, the halo radius $R_\odot$ and power-law index $t$ are determined by their fit to the observed DLA or Mg $\text{II}$ host galaxies at low redshift ($z < 1$) as $R_\odot = 42.86$ kpc and $t = 0.26$ for the DLA (Chen & Lanzetta 2003), and $R_\odot = 107.14$ kpc and $t = 0.35$ for the Mg $\text{II}$ system (Chen et al. 2010). Based on the semi-analytic models of galaxy evolution (e.g., Mo et al. 1999), the halo size of galaxies is expected to be smaller at higher redshift, which has also been confirmed in several observational studies of disk galaxies (e.g., Barden et al. 2005; Trujillo et al. 2006). Therefore, we used the radius $R$ derived from the above formula as an upper limit of the extension of the gas cloud associated with DLA or Mg $\text{II}$ host galaxies at $z \geq 2.0$. Figure 2 shows the apparent separation between the position of 27 detected galaxies in the $R$ band and the position of the afterglow as a function of their apparent magnitude (or $3\sigma$ upper limit) in the $K_s$ band, which corresponds to the rest-frame optical band at the redshift of the absorbers.

We also plot the upper limits of the halo radii associated with the DLA at $z = 3.564$, sub-DLA at $z = 3.022$, and Mg $\text{II}$ system at $z = 2.253$ and 1.773 based on the above formula. The magnitudes corresponding to $L_\odot$ are drawn from the rest-frame optical luminosity function as in Section 2.3. We found that three galaxies are located below the limit of the halo radius in Figure 2. We identified these three galaxies as candidates for the galaxies associated with the intervening DLA or Mg $\text{II}$ absorption systems toward GRB 050730. The three candidates are marked G1, G2, and G3 in Figures 1 and 2 in order of the apparent distance from the position of the afterglow. G1 and G2 are faint and were only detected in the deepest $R$-band image, whereas G3 is the brightest among the three candidates and was detected in all bands.

2.5. Photometric Color Selection

To further constrain the candidates for the host galaxies of the intervening absorbers, we used the stellar population synthesis models from Bruzual & Charlot (2003) and examined a possible evolutionary track in the two-color ($B-R$) versus ($R-K_s$) diagrams at each absorber’s redshift (Figure 3). Stellar ages in the tracks range from 1 Myr to the cosmic age at each redshift. Single-stellar population, exponentially decaying star formation
with e-folding time $\tau$ of 0.05, 0.1, 0.5, and 1 Gyr, and constant star formation models were used in the evolutionary tracks. We also used two different metallicities, $Z_\odot$, and $1/5Z_\odot$. We adopted the Salpeter (1955) initial mass function (IMF) with mass cutoffs of 0.1 and 100 $M_\odot$ for all cases. No dust attenuation was assumed, as typical DLAs show extremely low dust attenuation with $E(B-V) < 0.04$ (e.g., Ellison et al. 2005; Frank & Péroux 2010), and the attenuation should be negligible in this two-color diagram. In Figure 3, we also show the colors for the candidates G1, G2, and G3. For G1 and G2, because the exact $B$ and $K_s$ magnitudes were not available, we include the possible ranges of color expected from the $R$-band magnitude and the brightest limit of the $B$- and $K_s$-band magnitudes (see Table 1). We found that the color range for G1 (thin gray shaded area in Figure 3) overlaps with any type of evolutionary track at any redshift. The color of G3 (circle in Figure 3) can also be explained by the SED expected from the single-stellar population tracks at $z = 3.022$ and $z = 3.564$. These indicate that G1 could be a candidate for the galaxy associated with one of the four intervening absorbers, and G3 could be a candidate for the galaxy associated with either $z = 3.022$ (sub-DLA) or $z = 3.564$ (DLA) intervening absorbers. The color range for G2 (thick gray shaded area in Figure 3) overlaps with the evolutionary tracks at $z = 3.564$ and marginally overlaps with single-stellar population tracks at $z = 3.022$ at an age of around 40 Myr. This also indicates that G2 could be a candidate for the galaxy associated with either of the intervening absorbers at $z = 3.022$ (sub-DLA) or 3.564 (DLA). However, the impact parameter of G2 is larger than the size limit for the $z = 3.564$ DLA and too close to the size limit for the $z = 3.022$ sub-DLA. Thus, G2 is unlikely to be a galaxy associated with the intervening DLA or Mg II absorption systems toward GRB 050730.

2.6. Spectroscopy of the Brightest Candidate

To identify the redshift of the brightest object (G3), we performed optical spectroscopy with FOCAS mounted on the Cassegrain focus of the Subaru telescope (Kashikawa et al. 2002). We used a 0′.8 slit, 300B prism, and SY47 order-sort filter, which provided a wavelength coverage of 4800–9000 Å with a spectral resolution of $\sim 9.6$ Å, to identify the rest-frame UV spectral features of the absorbers at $z = 2.0$–3.5, such as Ly$\alpha$ emission, continuum depression near the Lyman limit, and several interstellar absorption features seen in the spectra of LBGs (Shapley et al. 2003). During target acquisition, we also took a $V$-band snapshot image of the field around GRB 050730, including the three candidates, using FOCAS (see Table 1). The total exposure times were 5400 s and 180 s for spectroscopy and snapshot imaging, respectively. Flux calibration and atmospheric absorption-band correction were performed using the spectrum of the spectrophotometric standard star GD153, obtained on the same night. The spectroscopic data were reduced in the standard manner using IRAF. We performed bias subtraction, overscan subtraction, flat fielding with a dome lamp flat, image distortion correction, wavelength calibration with a ThAr lamp, background subtraction, and sky background subtraction. Finally, the two-dimensional spectra were co-registered and combined, and then the one-dimensional spectrum of the object was extracted from the combined two-dimensional spectrum. In Figure 4, we show the resultant FOCAS spectrum of G3. We found no obvious rest-frame UV features in the obtained spectrum.

To further constrain the redshift of G3, we also estimated the photometric redshift of the galaxy based on the photometry in the $B, V, R, I, z', J, K_s$, and $L$ (3.6 $\mu$m) bands (points in Figure 4) using the publicly available software EAZY (Brammer et al. 2008). EAZY fits the observed SED of the galaxy with a combination of galaxy templates. We used the default EAZY template set eazy_v1.0, which consists of five templates that span the colors of galaxies in the semi-analytic model and an additional template to compensate for the lack of young and dusty galaxies in the semi-analytic model. Figure 4 shows the best-fit SED template, which is in good agreement with both the photometric points and the observed spectrum. The redshift of the best-fit SED is $z_{\text{phot}} = 0.519^{+0.028}_{-0.023}$. We also show the resulting $\chi^2$ as a function of the photometric redshift, which reaches a minimum at the redshift of the best-fit template ($z_{\text{phot}} = 0.519$). Therefore, we conclude that G3 is most likely at $z \sim 0.5$ and is not related to the known intervening absorbers.

3. Constraining the Properties of Intervening Absorbers

The above arguments suggest that G1 is most likely to be a host galaxy of one of the intervening absorbers toward GRB 050730, whereas G2 and G3 are unlikely to be related to the absorbers. In this section, we constrained the SFR and stellar mass for the four intervening absorbers at $z = 1.7$–3.5 toward GRB 050730 by assuming that (1) G1 is a host galaxy of the absorber at each redshift or (2) there is no detectable galaxy related to the absorbers. Finally, we compared the constrained SFR and stellar mass of the intervening absorbers at $z = 1.7$–3.5 with the other high-$z$ ($z > 2$) galaxy populations.
Figure 3. Evolutionary tracks in the two-color $(B-R)$ vs. $(R-K_s)$ diagrams at the redshift of the intervening absorbers from Bruzual & Charlot (2003) stellar population synthesis models. Stellar ages in the tracks range from 1 Myr to the cosmic age at each redshift. Single-stellar population (circles), exponentially decaying star formation with $e$-folding time $\tau$ of 0.05, 0.1, 0.5, and 1 Gyr (crosses, boxes, triangles, and asterisks, respectively), and constant star formation (diamonds) models are used in these tracks. No dust attenuation is assumed. The solid and dashed lines show the evolutionary tracks for metallicities of $Z_\odot$ and $1/50 Z_\odot$, respectively. Thin and thick gray shaded areas show the range of color expected from the 3$\sigma$ upper limit of the $B$- and $K_s$-band magnitudes (see Table 1) and the $R$-band magnitude of the candidate G1 ($R \sim 26.69$) and G2 ($R \sim 25.65$), respectively. The thick open circle shows the color of candidate 3.

Figure 4. Left: photometric measurements of candidate G3 (circles with error bars) and the best-fit SED (thin line) to the photometry data. The optical spectrum obtained by FOCAS is also plotted (thick line). Candidate G3 is most likely a low-redshift galaxy at $z \sim 0.5$. Right: $\chi^2$ value of the SED fitting as a function of the photometric redshift.

3.1. Star Formation Rate

We estimated SFRs of the galaxies associated with the intervening DLA or MgII absorption systems at $z = 1.773, 2.253, 3.022,$ and $3.564$ from the rest-frame UV continuum ($R$ band in the observed frame). We used the empirical formulae of Madau et al. (1998) assuming Salpeter (1955) IMF and no reddening. In Table 2, we show the SFR for the absorbing galaxy at each redshift in case (1), the case where G1 is a host galaxy of the absorbers. We also estimated the SFR using the 3$\sigma$ upper limit of the rest-frame UV continuum in case (2), the case that there is no galaxy associated with the absorbers. In all cases, we found that the SFR for the DLA galaxies at $z > 3$ was $\sim 2.5 M_\odot$ yr$^{-1}$ or smaller. At $z > 2$, Péroux et al. (2012) reported the upper limit of the SFR for typical less metal-rich DLA host galaxies ($Z \lesssim 0.1 Z_\odot$), which are similar in
Figure 5. Observed flux of G1 in the R band (cross, $R \sim 26.69$) and the 3σ flux upper limit in the $BVIJKsL$ bands (circles, see Table 1) are plotted as a function of the observed wavelength. We fit the model SEDs (solid lines) to the observed flux for the galaxies associated with the intervening DLA or Mg II absorbers at $z \sim 1.773, 2.253, 3.022$, and $3.564$. The model SEDs were drawn from the stellar population synthesis model of Bruzual & Charlot (2003) by considering a variety of star-formation histories (SFHs) including single-stellar populations, exponentially declining SFRs with e-folding timescales from 10 Myr to 5 Gyr, and constant star formation, and two different metallicities with $Z = Z_\odot$ and 0.02 $Z_\odot$. The models were computed for ages from 1 Myr to the cosmic age at each redshift. No dust reddening was assumed in the model SEDs. Fluxes of the model SEDs were scaled to fit the $R$-band flux of G1 (see the main text for details). Using the scaled flux and mass–luminosity ratio of the model SEDs, we constrained the stellar mass of the intervening DLA or Mg II host galaxies. The inset in each figure shows the distribution of the stellar masses derived from the model SEDs for each intervening absorber.

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

metallicity to our DLA ($z = 3.564$) and sub-DLA ($z = 3.022$) samples, using the upper limit of the Hα fluxes derived from the VLT/SINFONI IFU data. Our derived upper limit for less metal-rich DLA host galaxies is comparable to, or even more stringent than, that constrained by Péroux et al. (2012, $\sim 3.6 M_\odot$ yr$^{-1}$ assuming Salpeter IMF).

In the case of the $z \sim 2$ Mg II system ($W_{2796}^\prime \sim 1\AA$), we reached an SFR upper limit of $1.0 M_\odot$ yr$^{-1}$, but no host galaxies were clearly detected. By contrast, host galaxies of strong Mg II systems ($W_{2796}^\prime \sim 0.3\AA$) at $z \sim 1$ were detected with an SFR of more than $10 M_\odot$ yr$^{-1}$ (Lovegrove & Simcoe 2011). This difference in the SFR between $z \sim 1$ and $z \sim 2$ was also argued in Bouché et al. (2012) for the case of a very strong Mg II system with $W_{2796}^\prime \sim 2.0\AA$. They concluded that $z \sim 2$ Mg II absorbers reside in smaller halos than $z \sim 1$ systems. Although our sample size is only two, our result for the strong Mg II systems with $W_{2796}^\prime \sim 1.0\AA$ supports the scenario proposed in Bouché et al. (2012).

### 3.2. Stellar Mass

Using the GRB absorbers, we were able to strictly constrain the continuum flux of the intervening absorbers, as the background GRB afterglow used for identifying the absorbers had completely disappeared when we performed the deep imaging. Thus, we did not need to consider the ambiguity of the noise estimation arising from the background PSF subtraction. Moreover, we could eliminate the possibility that the galaxy associated with the absorbers was hidden in the unsubtracted core of the background PSF, even if there were no detectable galaxy around the position of the afterglow. These unambiguous constraints on the continuum level provide a unique opportunity to constrain the stellar mass of DLA or Mg II host galaxies at $z > 2$ for the first time.

The upper limits on the stellar masses associated with the intervening DLA or Mg II absorption systems at $z = 1.773, 2.253, 3.022$, and $3.564$ were derived by fitting the stellar
population synthesis models of Bruzual & Charlot (2003) to the upper limit for each object’s continuum flux. We used the same set of stellar population synthesis models as were used in Section 2.5. We derived the upper limit of the stellar mass at each redshift for two separate cases: (1) we assumed that G1 was a host galaxy of the absorber and (2) we assumed that no galaxy was associated with the absorber. Figure 5 shows the fitted model SEDs at each redshift of the intervening absorption systems as a function of the observed wavelength, assuming case (1). In the same figure, we also plot the flux of G1 in the R band and the 3σ upper limits on the fluxes in the other observing bands. In case (1), the model SEDs were scaled to fit the R-band flux of G1. In this case, we excluded any model SEDs whose scaled fluxes exceeded any of the 3σ upper limits for the observed bands other than the R band. In case (2), the model SEDs were scaled to avoid exceeding any of the 3σ upper limits in the observed bands. Table 2 summarizes the results of the stellar mass estimations. We found that the stellar mass of the DLA or Mg II absorbers at $z \gtrsim 2$ is less than a few times $10^8 M_\odot$, which is comparable to the mass of dwarf galaxies like LMC (Harris & Zaritsky 2009).

It should be noted that we derived upper limits on the stellar mass for the less metal-rich DLA at $z = 3.564$ ([Si/H] $< -1.3$) and sub-DLA at $z = 3.022$ ([Si/H] $= -1.5 \pm 0.2$) are consistent with the stellar masses predicted from the observed mass–metallicity relation for $z > 2$ star-forming galaxies (e.g., Savaglio et al. 2005; Maiolino et al. 2008).

3.3. Comparison with Other $z > 2$ Galaxy Populations

In this section, we compare the measured (or constrained) SFRs and stellar masses for the DLA and Mg II host galaxies at $z_{abs} \geq 2$ against those obtained for other $z > 2$ galaxy populations, such as LBGs (e.g., Reddy et al. 2006; Erb et al. 2006) and LAEs (e.g., Gawiser et al. 2006; Nilsson et al. 2007; Lai et al. 2008). To compare the distribution of their SFRs and stellar masses, we investigated their specific star formation rates (SSFRs). The SSFR is defined as the ratio between the SFR and the stellar mass, and it is an indicator of the intensity of star formation in the galaxy. In Figure 6, we plot the SSFR versus stellar mass for our DLA absorbers at $z > 3$ and Mg II absorbers at $z \sim 2$. Given that we do not identify a galaxy corresponding to each absorber, we constrained the SSFR for each absorber in two separate cases: (1) we assumed that G1 was a host galaxy of the absorber and (2) we assumed that no host galaxy was detected in our image. For all cases, we found that our absorbing galaxies were located between the low-mass end of LBGs and LAEs. This implies that our sample absorbers, which consist of less metal-rich ([Si/H] $< -1.0$) DLAs and Mg II systems, should not reside in the massive star-forming galaxies (like typical LBGs). Indeed, our derived SSFRs for the DLA/Mg II absorbers are consistent with the SSFRs of $z = 1.7–2.5$, less metal-rich DLAs, as derived from their abundance pattern using star formation histories (SFHs) similar to local irregular or dwarf starburst galaxies with weak star formation efficiency (Dessauges-Zavadsky et al. 2007; Calura et al. 2009).

4. CONCLUSIONS

We analyzed deep imaging data of the field around GRB 050730 in optical to mid-infrared wavelengths to identify the host galaxies giving rise to the intervening DLA and Mg II absorbers at $z = 1.773, 2.253, 3.022$, and 3.564. We used our own near-infrared and optical imaging data obtained with the Subaru telescope, together with archived optical and mid-infrared imaging data obtained with the VLT and Spitzer. We examined the color, impact parameter, and photometric redshift (for the brightest galaxy only) for the galaxies detected in our multi-color images to constrain the candidates for the galaxies associated with the intervening absorbers. We found no unambiguous candidate for the host galaxies in our data. Using the 3σ limiting flux or the flux of the marginally detected galaxy (G1) in the R-band image (corresponding to the UV wavelength in the rest frame of the intervening absorbers), we placed the following constraints on the upper limits of the SFR in the galaxies giving rise to the intervening absorbers: 2.5 $M_\odot$ yr$^{-1}$ for the DLA and sub-DLA systems and 1.0 $M_\odot$ yr$^{-1}$ for the Mg II systems. We used the 3σ upper limit of the flux in each wavelength to constrain the stellar mass of the absorbing galaxies to be several times $10^8 M_\odot$ or lower. We confirmed that the stellar mass limits for the DLA and sub-DLA at $z = 3.564$ and 3.022 are consistent with the stellar masses expected from their metallicity, assuming the mass–metallicity relation observed at $z > 3$ (Maiolino et al. 2008). Both the SFR and the stellar mass for the intervening absorbers show properties similar to dwarf galaxies like the LMC (Harris & Zaritsky 2009). The intervening absorbers in the direction of GRB 050730, which consist of the less metal-rich DLAs and Mg II systems with $W_{20796} \sim 1.0$ Å, show low SSFRs ($\lesssim 1.0$ Gyr$^{-1}$), which are comparable to LAEs or LBGs at the low-mass end of their mass function. This low SSFR for our intervening absorbers favors the scenario that typical DLAs and Mg II systems with low metallicities are likely to reside in dwarf galaxies, rather than in massive star-forming galaxies like typical LBGs.
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REFERENCES

Barden, M., Rix, H.-W., Somerville, R. S., et al. 2005, ApJ, 635, 959
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bouché, N., Murphy, M. T., Péroux, C., et al. 2012, MNRAS, 419, 2
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503
Brusa, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calura, F., Dessauges-Zavadsky, M., Prochaska, J. X., & Matteucci, F. 2009, ApJ, 693, 1236
Chen, H.-W., Helou, J. E., Gauthier, J.-R., et al. 2010, ApJ, 714, 1521
Chen, H.-W., & Lanzetta, K. M. 2003, ApJ, 597, 706
Churchill, C. W., Mellon, R. R., Charlton, J. C., et al. 2000, ApJS, 130, 91
Clowes, R. G., Irwin, M. J., & McMahon, R. G. 1997, ApJ, 475, 653
Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319
Dessauges-Zavadsky, M., Calura, F., Prochaska, J. X., & Matteucci, F. 2007, A&A, 470, 431
Ellison, S. L., Hall, P. B., & Lira, P. 2005, ApJ, 130, 1345
Erb, D. K., Steidel, C. C., Shapley, A. E., & Pettini, M. 2006, ApJ, 647, 128
Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189
Frank, S., & Peroux, C. 2010, MNRAS, 406, 2235
Fryxell, A. S., Levin, A. J., Strolger, L., et al. 2006, Nature, 441, 463
Fynbo, J. P. U., Laursen, P., Ledoux, C., et al. 2010, MNRAS, 408, 2128
Fynbo, J. P. U., Ledoux, C., Noterdaeme, P., et al. 2011, MNRAS, 413, 2481
Fynbo, J. P. U., Prochaska, J. X., Sommers-Larsen, J., Dessauges-Zavadsky, M., & Moel, P. 2008, ApJ, 683, 321
Fynbo, J. P. U., Muller, C., & Warren, S. J. 1999, MNRAS, 305, 845
Gawiser, E., van Dokkum, P. G., Gronwall, C., et al. 2006, ApJ, 642, L13
Harris, J., & Zaritsky, D. 2009, AJ, 138, 1243
Holland, S. T., Barthelmy, S., Burrows, D. N., et al. 2005, GRB Coord. Network, 3704, 1
Ilbert, O., Tresse, L., Zucca, E., et al. 2005, A&A, 439, 863
Kashikawa, N., Aoki, K., Asai, R., et al. 2002, PASJ, 54, 819
Lai, K., Huang, J.-S., Fazio, G., et al. 2008, ApJ, 674, 70
Landolt, A. U. 2009, AJ, 137, 4186
Laskar, T., Berger, E., & Chary, R.-R. 2011, ApJ, 739, 1
Ledoux, C., Pettijean, P., Fynbo, J. P. U., Muller, P., & Srianand, R. 2006, A&A, 457, 71
Leggett, S. K., Currie, M. J., Varricatt, W. P., et al. 2006, MNRAS, 373, 781
Lovegrove, E., & Simcoe, R. A. 2011, ApJ, 740, 30
Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 1006
Maiolino, R., Nagao, T., Grazian, A., et al. 2008, A&A, 488, 463
Marchesini, D., van Dokkum, P., Quadri, R., et al. 2007, ApJ, 656, 42
Metzger, M. R., Djorgovski, S. G., Kulkarni, S. R., et al. 1997, Nature, 387, 878
Mirabal, N., Halpern, J. P., Kulkarni, S. R., et al. 2002, ApJ, 578, 818
Miyazaki, S., Komiyama, Y., Sekiguchi, M., et al. 2002, PASJ, 54, 833
Mo, H. J., Mao, S., & White, S. D. M. 1999, MNRAS, 304, 175
Muller, P., Fynbo, J. P. U., & Fall, S. M. 2004, A&A, 422, L33
Muller, P., Warren, S. J., Fall, S. M., Fynbo, J. U., & Jakobsen, P. 2002, ApJ, 574, 51
Nilsson, K. M., Muller, P., Muller, O., et al. 2007, A&A, 471, 71
Noterdaeme, P., Laursen, P., Pettijean, P., et al. 2012, A&A, 540, A63
Noterdaeme, P., Pettijean, P., Ledoux, C., & Srianand, R. 2009, A&A, 505, 1087
Okoshi, K., & Nagashima, M. 2005, ApJ, 623, 99
Ouchi, M., Shimasaku, K., Okamura, S., et al. 2004, ApJ, 611, 660
Pandey, S. B., Castro-Tirado, A. J., McBreen, S., et al. 2006, A&A, 460, 415
Péroux, C., Bouché, N., Kulkarni, V. P., York, D. G., & Vladilo, G. 2012, MNRAS, 419, 3060
Péroux, C., McMahon, R. G., Srianand, R., L. J., & Irwin, M. J. 2003, MNRAS, 346, 1103
Pollack, L. K., Chen, H.-W., Prochaska, J. X., & Bloom, J. S. 2009, ApJ, 701, 1605
Prochaska, J. X., Chen, H.-W., Bloom, J. S., et al. 2011, ApJS, 168, 231
Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. 2007b, ApJ, 666, 267
Prochaska, J. X., & Wolfe, A. M. 2009, ApJ, 696, 1543
Rao, S. M., Belfort-Mihalyi, M., Turnshek, D. A., et al. 2011, MNRAS, 416, 1215
Rao, S. M., Nestor, D. B., Turnshek, D. A., et al. 2003, ApJ, 595, 94
Rao, S. M., Turnshek, D. A., & Nestor, D. B. 2006, ApJ, 636, 610
Reddy, N. A., Steidel, C. C., Fadda, D., et al. 2006, ApJ, 644, 792
Salpeter, E. E. 1955, ApJ, 121, 161
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
Steidel, C. C., Adelberger, K. L., Shapley, A. E., et al. 2003, ApJ, 592, 728
Suzuki, R., Tokoku, C., Ichikawa, T., et al. 2008, PASJ, 60, 1347
Tananaka, I., Breuck, C. D., Kurk, J. D., et al. 2011, PASJ, 63, 415
Trujillo, I., Förster Schreiber, N. M., Rudnick, G., et al. 2006, ApJ, 650, 18
Vreeswijk, P. M., Ellison, S. L., Ledoux, C., et al. 2004, A&A, 419, 927
Vreeswijk, P. M., Muller, P., & Fynbo, J. P. U. 2003, A&A, 409, L5
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Wolfe, A. M., Turnshek, D. A., Smith, H. E., & Cohen, R. D. 1986, ApJS, 61, 249
Yagi, M., Kashikawa, N., Sekiguchi, M., et al. 2002, AJ, 123, 66