Near-infrared Spectroscopy of GRB Host Galaxies at $z \gtrsim 1.5$: Insights into Host Galaxy Dynamics and Interpretations of Afterglow Absorption Spectra

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ABSTRACT

This paper presents near-infrared echellette spectra of faint galaxies in the fields around GRB 050820A at redshift $z = 2.613$ and GRB 060418 at $z = 1.490$. The spectroscopic data show that both GRBs originate in a dynamic environment of interacting galaxies separated by $< 15 \, h^{-1}$ kpc in projected distance and $|\Delta v| \lesssim 60 \, \text{km s}^{-1}$ in line-of-sight velocity. The optical afterglows revealed in early-epoch Hubble Space Telescope images are at least 2.5 $h^{-1}$ kpc (or 0.4′′) away from the high surface brightness regions of the interacting members, indicating that the GRB events occurred either in the outskirts of a compact star-forming galaxy or in a low surface brightness satellite. Comparisons of the systemic redshifts of the host galaxies and the velocity distribution of absorbing clouds revealed in early-time afterglow spectra further show that the majority of the absorbing clouds are redshifted from these compact star-forming galaxies. These include the gas producing fine-structure absorption lines at physical distances $d \sim a \times 100 \, \text{pc}$ from the GRB afterglow. The lack of blueshifted absorbing clouds and the spatial offset of the GRB event from the star-forming regions make it difficult to attribute the observed large velocity spread ($\sim 200 - 400 \, \text{km s}^{-1}$) of absorbing gas in the GRB host to galactic-scale outflows. We consider a scenario in which the GRB event occurred in a dwarf satellite of the interacting group and interpret the broad absorption signatures in the afterglow spectra as a collective effect of the turbulent halo gas and the host star-forming ISM. We briefly discuss the implications for the absorption properties observed in the afterglow spectra.

Key words: gamma-ray burst: individual: GRB 050820A – gamma-ray burst: individual: GRB 060418 – ISM: kinematics – galaxies: high-redshift: galaxies: formation – cosmology: observations.

1 INTRODUCTION

Optical afterglows of $\gamma$-ray bursts (GRBs) provide a novel alternative for probing the interstellar medium, galactic halos, and intergalactic gas in the distant universe (e.g. Vreeswijk et al. 2004; Chen et al. 2005a; Prochaska, Chen, & Bloom 2006; Vreeswijk et al. 2007; Chen et al. 2007a; Fox et al. 2008; D’Elia et al. 2009; Ledoux et al. 2009). Because long-duration GRBs are believed to originate in the catastrophic death of massive stars (e.g. Woosley & Bloom 2006) and because massive stars evolve rapidly, these GRBs also provide a powerful internal light source for probing young, active star-forming regions well into the epoch of re-ionization (e.g. Wijers et al. 1998; Tanvir et al. 2009; Salvaterra et al. 2009). Unlike quasars, optical afterglows disappear after a few months and do not hamper follow-up searches for GRB host galaxies and other faint galaxies near the afterglow sightlines, allowing direct comparison studies of ISM and stellar properties of distant galaxies.

Early-time afterglow spectra have revealed numerous absorption features due to resonance and fine-structure transitions that enable accurate measurements of the chemical composition, dust content, and kinematics of both GRB host galaxies and intervening galaxies along the lines of sight (e.g. Savaglio 2006; Prochaska et al. 2007). In particular, the absorption-line profiles have routinely shown complex gas kinematics in the GRB host environments (e.g. Prochaska et al. 2008a). The physical origin of the observed large ve-
velocity spread is unclear due to unknown emission properties of the host galaxies. But because of a massive star origin of GRB progenitors, a natural explanation for the observed large velocity spread in the gas foreground to the afterglows is starburst driven outflows. However, constraining the outflow velocity requires knowledge of the systemic velocity of the host galaxy.

Here we present results from a pilot program to obtain spectroscopic confirmation of GRB host galaxies at \(z \gtrsim 1.5\). The primary objective is to determine the systemic redshifts of the host galaxies for studying gas flows in the GRB host environment. At high redshift, prominent ISM emission lines, such as [O II]3728, H\(\beta\) 4862, and H\(\alpha\) 6564, are redshifted into the near-infrared wavelength range at \(\lambda > 0.9 \mu m\). Near-infrared spectroscopy of faint galaxies is challenging due to numerous strong atmospheric OH lines. To increase the efficiency of the spectroscopic program, we utilize a new near-infrared echellette spectrograph that offers sufficient resolution over a broad wavelength range from \(\lambda = 0.8 \mu m\) to \(\lambda = 2.5 \mu m\) for resolving galaxy emission features from OH skylines.

We have selected galaxies in the fields around GRB\(050820A\) at \(z = 2.613\) and GRB\(060418\) at \(z = 1.490\) for the pilot spectroscopic program. For each GRB, multi-epoch optical images of the field are available in the HST data archive that allow a precise and accurate determination (better than 0.05") of the location of the optical afterglow (e.g. Chen et al. 2009; Figure 1). Candidate host galaxies have been identified based on their proximity to the afterglow position in the HST images. In addition, high spectral resolution, high S/N early-time afterglow spectra are also available for the two events permitting detailed characterizations of the absorption properties of the host environment (Ellison et al. 2006; Prochaska et al. 2007, 2008a; Vreeswijk et al. 2007). We note that while spectroscopic confirmations are already available for a handful of GRB host galaxies at \(z \gtrsim 1.5\), including GRB\(971214\) at \(z = 3.42\) (Kulkarni et al. 1998), GRB\(000926\) at \(z = 2.04\) (Fynbo et al. 2002), GRB\(011211\) at \(z = 2.14\) (Fynbo et al. 2003), and GRB\(021004\) at \(z = 2.33\) (Jakobsson et al. 2005), these have been based on observations of Ly\(\alpha\) emission and do not yield an accurate systemic redshift of the host (e.g. Steidel et al. 2010). Near-infrared spectra of high-redshift GRB host galaxies have so far been available only for the host of GRB\(021004\) at \(z = 2.33\) (Castro-Tirado et al. 2010).

This paper is organized as follows. In Section 2, we describe the spectroscopic observations of faint galaxies in the targeted GRB fields and provide a summary of the data reduction and analysis procedures. In Section 3, we present the rest-frame optical spectra of the GRB host galaxies. In Section 4, we compare the systemic velocities of the host galaxies with the velocity distribution of gaseous clouds revealed in early-time afterglow spectra, and explore scenarios that explain the observed complex gas kinematics in GRB host environment. Finally, we discuss the implications of the spectroscopic observations in Section 5. We adopt a flat \(\Lambda\) cosmology, \(\Omega_M = 0.3\) and \(\Omega\Lambda = 0.7\), with a dimensionless Hubble constant \(h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})\) throughout the paper.

![Figure 1](image_url) Multi-epoch optical images of the field around GRB\(050820A\) (top) and the field around GRB\(060418\) (bottom) obtained using the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) and retrieved from the HST data archive (PID 10551; PI: S. Kulkarni). The early-intime image of the field around GRB\(050820A\) was obtained using ACS and the F850LP filter, and the late-intime image was formed by combining stacks of images obtained using the F625W, F775W, and F850LP filters. Galaxies A and B are discussed in §3.1 (see also Chen et al. 2009). The early-intime images of the field around GRB\(060418\) were obtained using ACS and the F775w filter, and the late-intime image was formed by combining stacks of images obtained using the F625W, F775W, and F850LP filters. Galaxies A, B, C, G1, G2, and G3 are discussed in §3.2 (see also Pollack et al. 2009). The optical transient (OT) in each field is apparent in the early-intime images (marked by the arrow). An extended, low surface brightness source is revealed at the location of GRB\(050820A\) in the late-intime image. No object is seen at the location of GRB\(060418\) in the late-intime image to a 5-\(\sigma\) limit of \(AB(F775W) = 27.2\) over a 0.5" diameter aperture.

2 NEAR-INFRARED ECHELLETTE OBSERVATIONS AND DATA REDUCTION

We observed faint galaxies in the field around GRB\(050820A\) and GRB\(060418\) using the Folded port InfraRed Echellette (FIRE) spectrograph (Simcoe et al. 2010) on the Magellan Baade Telescope. FIRE offers high throughput and high spectral resolution (FWHM \(\approx 50\) km s\(^{-1}\)) over a broad wavelength range from \(\lambda = 0.8 \mu m\) to \(\lambda = 2.5 \mu m\) in a single setup. It is therefore an efficient tool for studying faint galaxies at \(z \gtrsim 1\). Here we describe the observations and data reduction procedures.
2.1 FIRE Observations

The observations were carried out on the nights of 11 and 12 June 2011 using a 1” slit under mean seeing conditions of 0.5″. In echelle mode, FIRE offers a slit length of ≈ 6″ across the spatial direction. We were able to observe multiple galaxies in one set up to optimize the spectroscopic observing efficiency. For the field around GRB 050820A, we were able to orient the slit to include the low surface brightness host candidate of the GRB and the nearby compact galaxy. Observers were able to orient the slit to include the low surface brightness host candidate of the GRB and the nearby compact galaxy. For the field around GRB 050820A, we were able to orient the slit to include the group of galaxies that are likely the GRB host (galaxies G1, G2, and G3 in the bottom panel of Figure 1) and galaxy B (see also Pollack et al. 2009) that are at θ < 2″ from the afterglow sightline.

Exposures were taken in dithering (ABBA) mode in sets of four, each of 900 s duration. The separations between positions A and B were about 2.5″. Calibration frames for wavelength solution were obtained immediately after each set of science exposures using an internal ThAr lamp. We also observed a nearby A0V star every hour for calibrating the telluric features. Flat-field calibration frames were taken during the afternoon. Additional twilight flat-field frames were also obtained for correcting the non-uniform slit illumination pattern. A total exposure time of 3.5 hours was obtained for the echellette spectroscopic observations of faint galaxies around GRB 050820A. A total exposure time of 3 hours was obtained for the group of galaxies around GRB 060418.

2.2 Data Reduction

The FIRE spectral data were processed and reduced using a custom-built reduction pipeline. Data reduction and spectrum extraction of our FIRE frames are challenging owing to two separate factors. First, the echellette spectra are distorted both in the dispersion and cross-dispersion directions, and the spectral images contain numerous tilted OH emission lines in the sky background. Second, nearly all of our targeted galaxies are faint and exhibit little/no trace of continuum. Therefore, accurate spectral traces cannot be determined using the science exposures alone.

To overcome these difficulties, we modified a data reduction pipeline that was originally developed by George Becker for processing optical echellette spectral frames (see e.g. Chen et al. 2010). This data reduction pipeline utilizes a sky subtraction algorithm outlined in Kelson (2003), which takes advantage of the fine-sampling of sky lines afforded by tilted spectral images and determines an accurate two-dimensional model of the sky spectrum to be removed from individual frames. The slit tilt was determined empirically based on the locations of telluric standards along the cross-dispersion direction. A two-dimensional model of the wavelength solution in vacuum units was then determined using available ThAr frames and corrected for heliocentric motion. Based on a comparison with OH sky lines, we find that the accuracy of the wavelength solution is better than 1 Å.

To extract emission-line only spectra, the data reduction pipeline first determines a trace solution across all echellette orders using the telluric standard frames obtained close in time and location to the targeted galaxies. An offset along the slit is then applied to match the trace to the emission-line features seen in the two-dimensional sky-subtracted frames. The observed A0V telluric standard were also useful for calibrating the sensitivity functions of individual echellette orders. We determined the throughput function for each echellette order by calibrating the observed telluric standard to a model A0V spectrum.

To optimize the accuracy of sky-subtraction and the signal-to-noise of the final extracted spectra, we first performed sky subtraction in individual spectral images. Next, we registered the sky-subtracted science frames using emission-line features visible in the data and formed a stacked two-dimensional spectral image for each targeted galaxy. Individual echellette orders were then extracted from the stacked frame using a boxcar extraction routine, and calibrated using the sensitivity function derived from the observed telluric standard. A final spectrum of the galaxy was formed by coadding these flux-calibrated orders.

3 SPECTRAL PROPERTIES OF INDIVIDUAL GRB HOST GALAXIES

The FIRE observations provided a spectroscopic confirmation of the host galaxies of two GRBs at z ≳ 1.5. Here we present the rest-frame optical spectra of the hosts of GRB 050820A and GRB 060418 at z = 2.613 and z = 1.49, respectively, and compare the systemic velocities of the hosts with the velocity field of gaseous clouds revealed in early-time afterglow spectra.

3.1 The Host of GRB 050820A at z = 2.613

GRB 050820A was detected by Swift (Page et al. 2005). An optical transient (OT) was identified less than 1 hr after the trigger (Fox & Cenko 2005; Vestrand et al. 2006). High-resolution (δν ≈ 7 – 10 km s⁻¹) echelle spectra of the afterglow obtained shortly after the burst (Ledoux et al. 2005; Prochaska et al. 2007; Fox et al. 2008) allowed accurate measurements of the source redshift and chemical abundances in the ISM of the host galaxy. The GRB was found to occur at z = 2.6147. The host galaxy was found to contain a total neutral hydrogen column density of log N(HI) = 21.0 ± 0.1 and metallicity [S/H] = −0.63 ± 0.11 along the GRB sightline (Prochaska et al. 2007). The observed relative abundances [S/Fe] = +0.97 ± 0.09 suggests a dust-to-gas ratio in the host ISM comparable to what is seen in the Small Magellanic Cloud with a visual extinction of A_V ≈ 0.08. No trace of H2 was found despite the large N(HI) and moderate metallicity. The molecular fraction of the host ISM was constrained to be f_H2 ≡ 2N(H2)/[N(HI) + 2N(H2)] < 10⁻⁶.5 (Tumlinson et al. 2007). Finally, two strong Mg II absorbers were found at z = 0.692 and z = 1.430 with W(2796) = 2.99 ± 0.03 Å and W(2796) = 1.9 ± 0.1 Å in the rest frame, respectively (Prochaska et al. 2007).

Photometric properties of faint galaxies in the field around GRB 050820A have been studied by Chen et al. (2009) based on an analysis of available multi-epoch ACS images of the field in the HST data archive. These authors identified an extended low surface brightness galaxy at the
Figure 2. Observations of galaxies along the sightline toward GRB 050820A. The right panel shows the image of the field from the top panel of Figure 1. The image is rotated to orient the slit along the vertical direction. The cross marks the position of the optical afterglow observed in early-epoch ACS images (Figure 1). Galaxy A at angular distance \( \theta \approx 1.3'' \) and galaxy B at \( \theta \approx 0.4'' \) were considered likely Mg II absorbing galaxies at \( z = 1.43 \) and \( z = 0.69 \) (Chen et al. 2009). The dashed rectangle shows roughly the slit coverage of the FIRE observations. The left panel shows a portion of the stacked FIRE spectrum. At the top, we show a rectified two-dimensional spectral image. The OH sky lines have been subtracted, revealing two sets of emission-line features from galaxies A (top) and B (bottom). These emission lines are consistent with H\( \beta \) at \( z = 2.6128 \) and \( z = 2.6134 \) for galaxies A and B, respectively. The one-dimensional spectrum at the bottom shows the emission features from galaxy B as highlighted by vertical dashed lines. Contaminating sky residuals are dotted out for clarity. The 1-\( \sigma \) error spectrum is presented in the cyan histogram.

3.1.1 Rest-frame Optical Spectra of the Host Candidates

We present in the left panel of Figure 2 a portion of the stacked FIRE spectrum. The rectified two-dimensional spectral image over the observed wavelength range of \( \lambda = 1.75 - 1.815 \mu m \) is shown at the top and the extracted one-dimensional spectrum of galaxy B is shown at the bottom. The slit size and orientation of the FIRE observations (dashed rectangle in the right panel of Figure 2) allowed us to observe the candidate GRB host and galaxies A and B in a single set-up. We detect two sets of emission-line features that are offset in both spatial and spectral directions in the stacked FIRE spectral image (left panel of Figure 2). No trace of continuum emission is visible. The spatial separation of the emission lines is consistent with the spatial separation of galaxies A and B, although the low surface brightness candidate host and galaxy B are expected to be blended in ground-based data due to seeing.

The spectral features of galaxies A and B appear to be very similar. The emission lines are consistent with H\( \beta \) at \( \lambda \approx 23,712 \) Å (not shown in Figure 2) but not [O II] 3727, 3729 in the FIRE spectra. The known H-band brightness limit, \( AB(H) > 26 \), from Chen et al. (2009) constrains the rest-frame absolute B-band magnitude to be fainter than \( M_{AB}(B) - 5 \log h = -18.5 \) for both galaxies A and B. The angular separation between galaxies A and B, \( \theta = 1.78'' \), corresponds to a physical projected distance of \( \rho_{AB} = 10 h^{-1} \) kpc. The line-of-sight velocity offset between the two objects is \( \Delta v = 50 \pm 8 \) km s\(^{-1}\). Such small separations in projected distance and velocity space indicate that galaxies A and B are an interacting pair associated with the host of GRB 050820A at \( z = 2.613 \), and
that GRB 050820A occurred in either one of the galaxies or in a low surface brightness satellite.

3.1.2 The Velocity Field of Absorbing Clouds Along the GRB Sightline

The FIRE observations have revealed interacting galaxies (A, B, and possibly the extended low surface brightness feature in the top panel of Figure 1) in the vicinity of GRB 050820A. Here we compare the spatially and spectrally resolved galactic dynamics with the velocity distribution of gaseous clouds revealed in early-time afterglow spectra.

In Figure 3, we present a subsample of the absorption profiles of low- and high-ionization species associated with the host of GRB 050820A from early-time afterglow spectra (Prochaska et al. 2007). Zero velocity corresponds to \( z = 2.6134 \), the redshift of galaxy \( B \) at \( \theta = 0.44'' \) (corresponding to a projected distance of \( \rho = 2.5 \, h^{-1} \text{kpc} \)) from the GRB sightline in Figure 2. Galaxy A at \( \theta = 1.34'' \) (corresponding to a projected distance of \( \rho = 7.5 \, h^{-1} \text{kpc} \)) is found to offset from the systemic redshift of galaxy \( B \) by \( \Delta v = -50 \, \text{km s}^{-1} \).

The absorption profiles of the gas foreground to GRB 050820A are characterized by a large number of components, covering a velocity range from \( \Delta v = -140 \, \text{km s}^{-1} \) to \( \Delta v = +320 \, \text{km s}^{-1} \) of the host galaxies. The majority of the absorbing clouds appear to be redshifted from the systemic velocities of both members of the interacting system, including the dominant neutral gas component at \( \Delta v = +108 \, \text{km s}^{-1} \). In contrast, the highly ionized gaseous clump that produces the NV 1238, 1242 doublets appears to coincide in velocity space with galaxy \( B \).

3.2 The Host of GRB 060418 at \( z = 1.490 \)

GRB 060418 was detected by Swift (Falcone et al. 2006). The OT was identified nearly instantaneously after the trigger (Falcone et al. 2006). Echelle spectra of the afterglow obtained shortly after the burst revealed numerous low-ion resonant and fine-structure transitions that established the redshift of the GRB at \( z = 1.491 \) (Ellison et al. 2006; Prochaska et al. 2007; Vreeswijk et al. 2007). At this redshift, however, the host HI 1215 transition is not covered in ground-based spectra. The neutral hydrogen column density of the host is therefore unknown. The presence of abundant heavy ions, e.g. \( N(\text{Si II}) > 15.89 \) (Prochaska et al. 2007), suggests that the host ISM contains a neutral hydrogen column density of \( \log N(\text{HI}) > 20.3 \) for solar metallicity. The \( N(\text{HI}) \) limit would be still higher, if the gas contains sub-solar metallicity. The observed relative abundance \( [\text{Cr}/\text{Zn}] = -0.31 \pm 0.06 \) (Prochaska et al. 2007) also suggests a mild dust depletion (e.g. Pettini et al. 1997). Finally, this GRB sightline exhibits an extraordinarily high density of strong Mg II absorbers over a small redshift range. In addition to the host, three Mg II absorbers were found at \( z = 0.603, 0.656, \) and 1.107 with \( W(2796) = 1.27 \pm 0.01 \, \text{A}, 0.97 \pm 0.01 \, \text{A}, \) and 1.84 \pm 0.02 \, \text{A} \) in the rest frame, respectively (Prochaska et al. 2007).

Faint galaxies in the field around GRB 060418 have been studied by Pollack et al. (2009) based on an analysis of available multi-epoch ground-based and space-based broad-band images of the field. These authors identified an unusually high surface density of faint galaxies at \( \theta < 3.5'' \) from the GRB sightline in available ACS images from the HST data archive (Figure 1). This high surface density of faint galaxies appears to correspond to the large number of strong MgII absorbers revealed in early-time afterglow spectra. However, no object is found at the location of the OT (Figure 1). Given the consistent colors and possible interacting morphologies, Pollack et al. (2009) speculated that galaxies G1, G2, and G3 are an interacting galaxy group hosting the GRB and attributed galaxies A, B, and C to the strong MgII absorbers at lower redshifts.

Pollack et al. (2009) attempted optical spectroscopy of these faint galaxies and confirmed that galaxy A is indeed associated with the MgII absorber at \( z = 0.656 \). However, galaxies B and C remain unconfirmed due to a lack of spectral features in the optical data.
3.2.1 Rest-frame Optical Spectra of the Host Candidates

We present in the left panel of Figure 4 portions of the stacked FIRE spectrum. Rectified two-dimensional spectral images over the observed wavelength ranges of $\lambda = 1.205 - 1.225 \mu m$ and $\lambda = 1.615 - 1.640 \mu m$ are shown at the top and the extracted one-dimensional spectrum of galaxy G3 is shown at the bottom. The slit size and orientation of the FIRE observations (dashed rectangle in the right panel of Figure 4) allowed simultaneous observations of the candidate GRB host, G1, G2, and G3, and galaxy B in a single set-up. Galaxies G2 and G3 are expected to be blended in the FIRE observations due to seeing. Similar to the field of GRB050820A, we also detect two sets of emission-line features for the galaxies around GRB060418 that are offset in both spatial and spectral directions from each other in the stacked FIRE spectral image.

Figure 4 also shows a faint trace of continuum emission immediately adjacent to the emission features at the top of the spectral frame. A careful examination of the sky-subtracted, two-dimensional spectral image indicates that the continuum spectrum is spatially offset from the emission-line features. The spatial separation of the emission lines is consistent with the spatial separation of galaxies G1 and G2. We therefore interpret the continuum spectrum as due to galaxy B and the emission lines as due to galaxies G1 (top) and G3 (bottom). These emission lines are consistent with $[\text{O III}] 5008$ and $H\alpha$ at $z = 1.4901$ and $z = 1.4896$, respectively. Near these redshifts, the $[\text{O III}] 4960$ emission line is blended with a strong OH sky line. The observed $H$-band brightness limit, $AB(H) > 25$, from Pollack et al. (2009) constrains the rest-frame absolute $B$-band magnitude to be fainter than $M_{AB}(B) = -5 \log h - 18.4$ for galaxy G3. The angular separation between galaxies G1 and G3, $\theta = 2.15''$, corresponds to $\rho_{G13} = 12.7 h^{-1}$ kpc. The line-of-sight velocity offset between the two objects is $\Delta v = 60 \pm 8 \ km\ s^{-1}$. Similar to the configuration of the host of GRB050820A, such small separations in projected distance and velocity space indicate
that galaxies G1 and G3 (and likely G2) are an interacting group, hosting GRB 060418 at $z = 1.490$.

### 3.2.2 The Velocity Field of Absorbing Clouds Along the GRB Sightline

Similar to the field around GRB 050820A, the FIRE observations have revealed interacting galaxies in the vicinity of GRB 060418 (G1 and G3 in the bottom panel of Figure 1). Here we compare the spatially and spectrally resolved galactic dynamics with the velocity distribution of gaseous clouds revealed in early-time afterglow spectra.

In Figure 5, we present a subsample of the absorption profiles of low- and high-ionization species associated with the host of GRB 060418 from early-time afterglow spectra (Prochaska et al. 2007). Zero velocity corresponds to $z = 1.4896$, the redshift of galaxy G3 at $\theta = 0.53''$ (corresponding to a projected distance of $\rho = 3.1 \, h^{-1} \, \text{kpc}$) from the GRB sightline in Figure 3. Galaxy G1 at $\theta = 2.01''$ (corresponding to a projected distance of $\rho = 11.9 \, h^{-1} \, \text{kpc}$) is found offset from the systemic redshift of galaxy G3 by $\Delta v = +60 \, \text{km} \, \text{s}^{-1}$.

The absorption profiles of the gas foreground to GRB 060418 are characterized by a classic ‘edge-leading’ signature, with the dominant neutral gas components occurring at $\Delta v \approx +60 \, \text{km} \, \text{s}^{-1}$ and a blueshifted tail (most prominent in the Mg II and C IV absorption transitions) extending to $\Delta v = -140 \, \text{km} \, \text{s}^{-1}$ from the systemic velocity of galaxy G3. In this case, the dominant absorbing components as indicated by the low-ionization resonance and fine-structure transitions Ni II 1741 and Fe II 2389 appear to coincide in velocity space with galaxy G1 at nearly $4\times$ the projected distance of G3 from the afterglow sightline.

An edge-leading absorption profile is often considered a signature of an underlying rotating disk (e.g. Lanzetta & Bowen 1992). Recall that the GRB afterglow is an internal source that probes only part of the host ISM. The matching features are dotted out for clarity. Zero velocity corresponds to $z = 1.4896$, the redshift of galaxy G3 at $\theta = 0.53''$ (corresponding to a projected distance of $\rho = 3.1 \, h^{-1} \, \text{kpc}$) from the GRB sightline in Figure 3. Galaxy G1 at $\theta = 2.01''$ (corresponding to a projected distance of $\rho = 11.9 \, h^{-1} \, \text{kpc}$) is found off set from the systemic redshift of galaxy G3 by $\Delta v = +60 \, \text{km} \, \text{s}^{-1}$. This GRB host also exhibits complex line-of-sight gas kinematics with multiple components spreading over a velocity range from $\Delta v = -140 \, \text{km} \, \text{s}^{-1}$ to $\Delta v = +120 \, \text{km} \, \text{s}^{-1}$. The dominant absorbing components occur at $\Delta v = +60 \, \text{km} \, \text{s}^{-1}$, as indicated by the low-ionization resonance and fine-structure transitions Ni II 1741 and Fe II 2389. These low-ionization species appear to coincide in velocity space with galaxy G1.

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**Figure 5.** A subsample of the absorption profiles of low- and high-ionization species associated with the host of GRB 060418 from early-time afterglow spectra (Prochaska et al. 2007). Contaminating features are dotted out for clarity. Zero velocity corresponds to $z = 1.4896$, the redshift of galaxy G3 at $\theta = 0.53''$ (corresponding to a projected distance of $\rho = 3.1 \, h^{-1} \, \text{kpc}$) from the GRB sightline in Figure 3. Galaxy G1 at $\theta = 2.01''$ (corresponding to a projected distance of $\rho = 11.9 \, h^{-1} \, \text{kpc}$) is found offset from the systemic redshift of galaxy G3 by $\Delta v = +60 \, \text{km} \, \text{s}^{-1}$. This GRB host also exhibits complex line-of-sight gas kinematics with multiple components spreading over a velocity range from $\Delta v = -140 \, \text{km} \, \text{s}^{-1}$ to $\Delta v = +120 \, \text{km} \, \text{s}^{-1}$. The dominant absorbing components occur at $\Delta v = +60 \, \text{km} \, \text{s}^{-1}$, as indicated by the low-ionization resonance and fine-structure transitions Ni II 1741 and Fe II 2389. These low-ionization species appear to coincide in velocity space with galaxy G1.

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4 DYNAMICS OF GRB HOST GALAXIES

Combining the systemic velocities of the host star-forming regions and the line-of-sight velocity distributions of gaseous clouds in front of the GRB afterglows has allowed us to establish an absolute velocity field for the host galaxies of GRB 050820A and GRB 060418. The observed velocity field together with known ISM and stellar properties of the host galaxies offers important insights into the galactic environment of GRB hosts and the nature of the complex gas kinematics revealed in afterglow absorption spectra.

A unique aspect in afterglow absorption-line studies is the presence of excited ions in the host ISM as a result of UV pumping by the GRB afterglow (e.g. Prochaska, Chen, & Bloom 2006; Dessauges-Zavadsky et al. 2006; Vreeswijk et al. 2007, 2011). Given known radiation field from light-curve observations of the optical transient and the observed abundances of these excited ions, we have constrained the physical distance of the dominant neutral absorbing component, such as the component at $\Delta v = +108 \, \text{km} \, \text{s}^{-1}$ for GRB 050820A in Figure 3 and the components at $\Delta v = +60 \, \text{km} \, \text{s}^{-1}$ for GRB 060418 in Figure 5, at $d \sim$ a few $\times$ 100 pc. This distance scale places these neutral gaseous clouds outside of the birth cloud of the GRB progenitor but still within the same star-forming region where the progenitor star formed.

In the case of GRB 050820A, the majority of the absorbing clouds, including the gas at $d \sim$ a few $\times$ 100 pc from the GRB afterglow, are observed to be redshifted from both galaxies A and B at projected distances $\rho = 2.5 - 7.5 \, h^{-1} \, \text{kpc}$ away. In the case of GRB 060418, the majority of the absorbing clouds are also found to be redshifted from galaxy G3 at merely $\rho = 3.1 \, h^{-1} \, \text{kpc}$ away. The neutral gaseous
clouds at $d \sim a few \times 100$ pc from the GRB progenitor coincide with the systemic velocity of $G1$ at $\rho = 11.9 \ h^{-1}$ kpc away, nearly $4 \times$ the projected distance of $G3$.

In both cases, the GRB did not occur in the brightest regions of their host galaxies (cf. Fruchter et al. 2006). Instead, they were either in the outskirts of a compact star-forming galaxy or in a low surface brightness satellite. If they were in the outskirts of one of the interacting galaxies, then the lack of blueshifted absorbing components relative to the systemic velocities of the galaxies makes it difficult to attribute the observed complex gas kinematics along the afterglow sightline to galactic-scale outflows from the interacting galaxies. We note that although blueshifted absorbing components are seen relative to $G3$ along the GRB 060418 sightline, the HST images clearly show a spatial offset between the GRB event and the interacting members $G2$ and $G3$ (Figure 1). Different from the self-absorption seen in distant star-forming galaxies (e.g. Weiner et al. 2009), the GRB sightline does not probe directly into the compact star-forming regions. While outflows from galaxies $G1$ and $G3$ may contribute to some of the absorption components at the blue end, outflows alone is difficult to explain the ‘edge-leading’ absorption signatures along the afterglow sightline (Figure 5).

To understand the origin of the observed gas kinematics, we continue the discussion assuming that the GRBs occurred in a nearby dwarf satellite of the spectroscopically identified interacting galaxies. We focus on GRB 050820A as an example but the same scenario can be applied to explain the observations of GRB 060418. We illustrate the relative alignment in the cartoon shown in Figure 6.

We consider scenarios in which the interacting galaxies are either in the background or foreground of the host star-forming region. If the GRB arises in a satellite ($S$ shown in grey in Figure 6) in front of the interacting galaxies, then the observed redshifted motion of the host ISM relative to galaxies $A$ and $B$ suggests that the host satellite galaxy is falling toward the interacting galaxies. In this scenario, the GRB sightline does not probe the ISM of either galaxy $A$ or $B$, but only the local star-forming ISM of the GRB progenitor and halo gas. If the host star-forming region is behind the interacting galaxies, then the observed redshifted motion of the host ISM suggests that the GRB arises in a tidal dwarf galaxy ($S$ shown in dark) escaping galaxy $B$ as galaxies $A$ and $B$ interact each other. In this scenario, the star-forming region local to the GRB progenitor, the ISM of the interacting galaxies, tidal debris, and accreted halo gas are all expected to contribute to the absorption features in the afterglow spectra.

5 DISCUSSION

Near-infrared echellette spectra presented here have allowed us to go beyond a spectroscopic confirmation of two $z \gtrsim 1.5$ GRB host galaxies and obtain an accurate and precise measurement of the systemic redshifts of the host galaxies for studying gas flows in the GRB host environment. We find that the hosts of GRB 050820A and GRB 060418 share three common features.

First, both GRBs are found to originate in a dynamic environment of interacting galaxies separated by $10 \sim 12 \ h^{-1}$ kpc in projected distances and $|\Delta v| \lesssim 60 \ km \ s^{-1}$ in line-of-sight velocity separation. We have interpreted the high surface brightness star-forming regions as merging galaxies based primarily on the optical morphologies (Figure 1). While it is also possible that these compact sources are star-forming regions within the same galaxy, we consider this an unlikely scenario given the observed morphologies and the projected separations of $\sim 2''$ or $\sim 10 \ h^{-1}$ kpc. Previous studies based on deep HST images have shown that star-forming galaxies at $z = 2 - 3$ have on-average half-light radii of $\approx 0.2''$ (e.g. Bouwens et al. 2004) or $\approx 1.1 \ h^{-1}$ kpc (e.g. Rafeski et al. 2011; Law et al. 2011). Under a single object scenario, the projected distances observed between $A$ and $B$ around GRB 050820A or between $G1$ and $G3$ around GRB 060418 would imply a galaxy that is at least five times the typical size of $z \sim 2$ galaxies.

The optical morphologies of the host galaxies of
GRB 000926 at $z = 2.04$ and GRB 011211 at $z = 2.14$, displaying a similarly distorted morphology of interacting objects. Together they show that a large fraction (4/10) of known GRB host galaxies at $z \gtrsim 1.5$ (Kuulkarni et al. 1998; Jensen et al. 2001; Fynbo et al. 2002; Fynbo et al. 2005; Vreeswijk et al. 2004, 2006; Chen et al. 2009, 2010) may arise in interacting galaxies. Superstar clusters are commonly seen in interacting galaxies (e.g. de Grijs et al. 2002), which serve as a natural birth place for the progenitors of GRBs (e.g. Chen et al. 2007b).

Second, the majority of the absorbing gaseous clouds observed in the early-time afterglow spectra, including the gas producing fine-structure absorption lines at $d \sim a few \times 100$ pc from the GRB afterglow, are found to be redshifted from the interacting galaxies. This is different from what is seen in the host of GRB 021004 at $z = 2.33$, for which all of the absorbing gaseous clouds observed in the early-time afterglow spectra are found to be blueshifted from the systemic velocity of the host galaxy over the range of $|\Delta v| = 100 - 800$ km s$^{-1}$. At low redshifts, such kinematic study is known only for the host of GRB 030329 at $z = 0.18687$, which shows absorption components primarily blueshifted from the systemic velocity up to $|\Delta v| = 200$ km s$^{-1}$ (Thöne et al. 2007).

Recall that GRB afterglows serve as an internal light probe of the host galaxies. The predominantly redshifted motion found for the gas in front of GRB 050820A and GRB 060418 therefore suggests inflows. Likewise, the observed blueshifted motion in GRB 021004 and GRB 030329 suggests outflows. The mixture of blueshifted and redshifted gas on velocity scales greater than 200 km s$^{-1}$ in front of the GRB progenitor site underscores the complex and turbulent gas inflows and outflows around distant young star-forming galaxies (e.g. Haehnelt et al. 1998; Agertz et al. 2009). This is different from a more organized rotational motion seen in some damped Ly$\alpha$ absorbing galaxies (Chen et al. 2005b).

Finally, GRB 050820A and GRB 060418 did not occur in the brightest star-forming regions of their host galaxies like GRB 000926, GRB 011211, or other long-duration bursts (cf. Fruchter et al. 2006). In contrast, the closest, high surface brightness star-forming region is found to be at least $\rho = 2.5$ h$^{-1}$ kpc (or 0.4$''$) away, roughly three times the median projected offset found for long-duration GRBs (e.g. Bloom et al. 2002). This spatial offset and the lack of blueshifted absorbing systems relatively to the star-forming members suggest that the GRB event occurred in a low surface brightness tidal tail or satellite. If GRB 050820A arises in a tidal tail of galaxy $B$ as galaxies $A$ and $B$ approach each other (Figure 6), then the observed strength and velocity offset of the N V 1238, 1242 absorption doublets can be naturally explained by the conduction interface of stripped gas (e.g. Indebetouw & Shull 2004) from the interacting galaxies (cf. Prochaska et al. 2008b).

In addition, satellite galaxies or tidal tails contain relatively more pristine gas around otherwise chemically evolved star-forming galaxies (e.g. Thilker et al. 2009). The broad range of galactic environment probed by GRB events, from the luminous host example of GRB 021004 to possible faint dwarf satellites for the hosts of GRB 050820 and GRB 060418, is qualitatively consistent with the large scatter observed in the ISM metallicity of GRB host galaxies. (e.g. Savaglio 2010). The large velocity spread and low metallicity expected in tidal tails may also explain the large scatters seen in the velocity–metallicity correlation (Prochaska et al. 2008a; Ledoux et al. 2006).

In summary, we show that comparisons of the systemic redshifts of the host galaxies and the velocity distribution of absorbing clouds revealed in early-time afterglow spectra provide new insights into the nature of GRB host galaxies and their environments. Galactic-scale winds are not the only factor that drives the observed large velocity spread of gaseous clouds along GRB sightlines. Four of 10 GRB hosts known at $z \gtrsim 1.5$ exhibit similar morphologies showing interacting galaxies. Galaxy interactions can be effective in producing chemically enriched materials away from more concentrated star-forming regions found in deep galaxy surveys.

Lastly, we also note that the absorbing galaxies responsible for the two strong Mg II absorbers at $z = 0.692$ ($W(2796) = 2.99 \pm 0.03$ Å) and $z = 1.430$ ($W(2796) = 1.9 \pm 0.1$ Å) remain missing around the sightline toward GRB 050820A. No galaxies brighter than $AB(F775W) = 27.5$ (over a 0.5$''$ diameter aperture) are seen at $\theta < 3.5$ $''$ of the afterglow sightline in late-time HST ACS images. Either the absorbing galaxies are extremely faint < 0.03L$_{\odot}$, or we are seeing a large collection of absorbing clouds at projected distance $\rho \gtrsim 20$ h$^{-1}$ kpc from a star-forming galaxy.

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NIR Spectra of Two $z \gtrsim 1.5$ GRB Hosts
