A SURVEY FOR N v ABSORPTION AT z ≈ z^GRB IN GRB AFTERGLOW SPECTRA: CLUES TO GAS NEAR THE PROGENITOR STAR

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ABSTRACT

We survey N v absorption in the afterglow spectra of long-duration gamma-ray bursts (GRBs) with the intent to study highly ionized gas in the galaxies hosting these events. We identify a high incidence (6/7) of spectra exhibiting N v absorption with \( z \approx z^GRB \), and the majority show large column densities \( N(N^{+4}) \gtrsim 10^{14} \text{ cm}^{-2} \). With one exception, the observed line profiles are kinematically “cold”; i.e., they are narrow and have small velocity offset (\( \delta v \lesssim 20 \text{ km s}^{-1} \)) from absorption lines associated with neutral gas. In addition, the N v absorption has similar velocity to that of the UV-pumped fine-structure lines, indicating that these high ions are located within \( \lesssim 1 \text{ kpc} \) of the GRB afterglow. These characteristics are unlike those for N v absorption detected in the halo/disk of the Milky Way or along sight lines through high-\( z \) damped Ly \( \alpha \) systems but resemble the narrow absorption line systems associated with quasars and some high-\( z \) starbursts. We demonstrate that GRB afterglows photoionize nitrogen to \( N^{+4} \) at \( r \approx 10 \text{ pc} \). This process can produce N v absorption with characteristics resembling the majority of our sample, and we argue that it is the principal mechanism for \( N^{+4} \) along GRB sight lines. Therefore, the observations provide a snapshot of the physical conditions at this distance. In this scenario, the observations imply that the progenitor’s stellar wind is confined to \( r < 10 \text{ pc} \), which suggests that the GRB progenitors occur within dense (\( n \gtrsim 10^3 \text{ cm}^{-3} \)) environments, typical of molecular clouds. The observations, therefore, primarily constrain the physical conditions—metallicity, density, velocity fields—of the gas within the (former) molecular cloud region surrounding the GRB.

Subject headings: gamma rays: bursts — ISM: general

Online material: color figures

1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs) are believed to have massive star progenitors arising in active star-forming regions of high-\( z \) galaxies (e.g., Woosley & Bloom 2006). Roughly half of these events have associated UV/optical afterglows, and a subset of these have apparent magnitudes sufficient for high-resolution spectroscopy using 10 m class telescopes (e.g., Fiore et al. 2005; Chen et al. 2005). In principle, the power-law afterglow spectrum has imprinted within it features from gas through the interstellar medium (ISM) of the host galaxy. This stands in contrast to studies of quasars, whose integrated photon output ionizes their ISM and surrounding gas out to many tens of kiloparsecs. Furthermore, although quasar sight lines frequently penetrate foreground, star-forming galaxies (the so-called damped Ly \( \alpha \) systems [QSO-DLAs]; Wolfe et al. 2005), these are probed according to gas cross section and quasar sight lines should only rarely intersect the small, dense regions undergoing active star formation (Zwaan & Prochaska 2006).

In these respects, GRB afterglow spectra allow one to probe a diversity of phases in the ISM of star-forming galaxies: the circumstellar material from the massive star progenitor, the H ii region produced by the progenitor and neighboring OB stars, the neutral ISM of the host galaxy, and any diffuse gas within the galactic halo. Unfortunately, even though these phases arise at distinct distances along the sight line, the observed spectrum resolves only the relative velocities of the gas. To focus analysis on a specific phase, one is generally forced to isolate a unique ion and/or material associated with a specific velocity.

GRB afterglow spectra reveal large column densities of H i gas and metals associated with the host galaxy ISM (Savaglio et al. 2003; Vreeswijk et al. 2004; Jakobsson et al. 2006). The analysis of the metal line transitions has localized this neutral gas within the ambient ISM of the host galaxy. Specifically, the detection of fine-structure lines of Si ii and Fe ii ions places the gas within \( \approx 1 \text{ kpc} \) of the GRB afterglow while the detection of Mg i absorption requires the gas to lie at distances greater than \( \approx 100 \text{ pc} \) (Prochaska et al. 2006). These conclusions are supported by direct distance determinations based on analysis of line variability in fine-structure lines (\( \approx 100 \text{ pc} \) and 2 kpc from GRB 020813 and GRB 060418, respectively; Dessauges-Zavadsky et al. 2006; Vreeswijk et al. 2007). The majority of afterglow spectra also show high-ion absorption (e.g., C iv) that is offset by several tens to hundreds of kilometers per second from the peak optical depth of the neutral ISM (Chen et al. 2007c). This diffuse, ionized gas is also traced by strong transitions of low ions (e.g., Si ii 1526) but without coincident fine-structure absorption. Therefore, the gas must lie at distances greater than a few kiloparsecs from the GRB. These characteristics identify the clouds as partially ionized gas within the halo of the GRB host galaxy (Prochaska et al. 2008). While studies of the gas in the neutral ISM and galactic halo are valuable for studying the physical conditions in star-forming galaxies, these phases offer only indirect constraints on the nature of the GRB progenitor (Ramírez-Ruiz et al. 2002). Of great interest is to identify gas located within the star-forming region or even gas shed by the progenitor itself. To date, however, no study has presented compelling evidence for gas within \( \approx 100 \text{ pc} \) of the GRB: neither circumstellar material (Chen et al. 2007c), the molecular cloud that presumably beget the progenitor (Tumlinson et al. 2007), nor material associated with a preexisting H ii region.
(Whalen et al. 2008). Regarding the latter phase, most of the key diagnostics (e.g., Si iv, Al iii, Si iii, C iv) either are compromised by blending with the Lyα forest or can be confused with a galactic halo component. At present, there is only indirect evidence for significant column densities of ionized gas near GRBs: a number of GRB sight lines exhibit X-ray absorption with implied metal column densities measured from the optical spectra (Galama & Wijers 2001; Watson et al. 2007). This result hints at a large reservoir of highly ionized gas near the GRB that has not yet been revealed by the rest-frame UV spectra acquired by ground-based facilities.

The challenge to identify and study gas close to the GRB has motivated us to survey GRB afterglow spectra for the presence of N v absorption. Because the N v ion has a large ionization potential (IP = 77 eV), it is difficult to produce N v, especially using stellar radiation fields. In the ISM of local galaxies, N v is generally believed to trace collisionally ionized gas either in equilibrium at a high temperature (T > 10^6 K) or out of equilibrium due to a postshocked gas cooling from T > 10^6 K (e.g., Indebetouw & Shull 2004a). In terms of GRB studies, however, the GRB event itself and its bright afterglow emit sufficient numbers of hv ≈ 80 eV photons to produce N v gas near the progenitor. Observationally, the N v doublet is notable for exhibiting an alkali doublet at λλ1238, 1242 in the rest frame that lies redward of the H i Lyα transition. In GRB sight lines, therefore, this transition (unlike O v and S v doublets) does not blend with H i absorption from the Lyα forest, and GRB afterglow spectra that cover Lyα will often provide an analysis of the N v doublet. Indeed, previous studies have reported the detection of the N v doublet along individual sight lines (Vreeswijk et al. 2004; Chen et al. 2005; Thöne et al. 2008).

In this paper we perform a systematic search and analysis of N v gas for a modest sample of z > 2 GRBs. We report on the incidence of its detection and its characteristic column density and compare the line profiles with other transitions identified along the sight line. Finally, we investigate the origin of this gas and explore constraints on the nature of the GRB progenitor environment.

2. A SURVEY FOR N v ABSORPTION IN GRB SIGHT LINES

2.1. The GRB Sample

Our sample is comprised of all the published and/or publicly available GRB afterglow spectra that have resolution R > 2500 (FWHM < 120 km s^-1) and coverage of the Lyα profile and N v doublet from the ISM of the GRB host galaxy. This resolution criterion ensures that the N v doublet is well resolved, and it also establishes a sensitive detection limit: all of the data sets have a 1 σ equivalent width limit of 30 mÅ (or better) corresponding to N(N v) = 10^{13.15} cm^-2. The sample is summarized in Table 1, and the measured abundances are presented in Table 2. Figure 1 shows the corresponding line profiles. In every case except GRB 060206, where we adopt the values reported by Thöne et al. (2008), we measured the rest-frame equivalent width of the N v 1238 transition and derived the N v column density using line

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### TABLE 1

| GRB              | R.A.     | Decl.       | Instrument | R   | Ref. |
|------------------|----------|-------------|------------|-----|------|
| GRB 021004       | 00 26 54.68 | +18 55 41.60 | VLT UVES   | 52000 | 1    |
| GRB 030323       | 11 06 09.40 | −21 46 13.2  | VLT FORS2  | 2600  | 2    |
| GRB 050730       | 14 08 17.14 | −03 46 17.8  | Magellan MIKE | 30000 | 3    |
| GRB 050820       | 22 29 38.11 | +19 33 37.1  | Keck HIRES | 30000 | 4    |
| GRB 050922C      | 19 55 54.48 | −08 45 27.5  | VLT UVES   | 30000 | 5    |
| GRB 060206       | 13 31 43.42 | +35 03 03.6  | WHT ISIS   | 4000  | 6    |
| GRB 060607       | 21 58 50.40 | −22 29 46.68 | VLT UVES   | 43000 | 7    |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

References.—(1) Fiore et al. 2005; (2) Vreeswijk et al. 2004; (3) Chen et al. 2005; (4) Prochaska et al. 2007c; (5) Piranomonte et al. 2008; (6) Thöne et al. 2008; (7) Ledoux et al. 2006.

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### TABLE 2

| GRB              | z_{GRB}   | log N_{H1} (cm^-2) | [M/H]a     | W_{1238}b (Å) | log N(N v)c (cm^-2) | Δ(N v)d (km s^-1) |
|------------------|-----------|--------------------|------------|--------------|---------------------|------------------|
| GRB 021004       | 2.3291    | 19.00              | 0.0        | 0.307 ± 0.008 | 14.64 ± 0.04        | −10 ± 10         |
| GRB 030323       | 3.3720    | 21.90              | >−0.9      | 0.325 ± 0.043 | >14.35              | 20 ± 30          |
| GRB 050730       | 3.9686    | 22.15              | −2.3       | 0.142 ± 0.021 | 14.09 ± 0.08        | 5 ± 5            |
| GRB 050820       | 2.6147    | 21.00              | −0.6       | 0.045 ± 0.007 | 13.45 ± 0.05        | −90 ± 10         |
| GRB 050922C      | 2.1990    | 21.60              | −2.0       | 0.197 ± 0.026 | >14.19              | −20 ± 5          |
| GRB 060206       | 4.0480    | 20.85              | −0.9       | 0.093 ± 0.010 | 13.73 ± 0.15        | 0 ± 15           |
| GRB 060607       | 3.0748    | 16.80              | 0.0        | −0.009 ± 0.003 | <12.61              | ...              |

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a Gas metallicity derived from low-ion absorption. See Prochaska et al. (2007a) and M. Dessauges-Zavadsky et al. (2008, in preparation) for details.
b Rest-frame equivalent width of the N v 1238 transition.
c Estimated velocity offset between the rough centroid of the N v line profile and the peak optical depth of the fine-structure lines.
profile fitting techniques and/or the apparent optical depth method (Savage & Sembach 1991). In all but one case (GRB 060607), we report the positive detection of an N\textsubscript{v} doublet within 100 km s\textsuperscript{-1} of the peak optical depth of the low-ion gas. We associate this gas to the GRB host galaxy.

There are several common characteristics of the sample. First, the peak optical depth and the integrated column densities are large: five of the seven sight lines exhibit saturated N\textsubscript{v} absorption indicative of a column density \(N(\text{N}^{+4}) \gtrsim 10^{14} \text{ cm}^{-2}\). Second, these same cases have relatively narrow line profiles that are aligned or nearly aligned with the peak optical depth of the low-ion profiles. These characteristics are suggestive of a photoionized gas. Third, the N\textsubscript{v} profiles generally coincide in velocity with the fine-structure lines. By association, we argue that the majority of N\textsuperscript{+4} gas is located within \(\lesssim 1\) kpc of the GRB event (Prochaska et al. 2006). Finally, there are no significant trends between the characteristics of the N\textsuperscript{+4} gas and the ISM metallicity, GRB redshift, or the H\textsc{i} column density or the metal column density of the ambient ISM.

Two of the seven sight lines do not follow the general trends described above. The first (GRB 060607) does not exhibit any N\textsubscript{v} absorption to very low limits. This sight line is unique for having a very low H\textsc{i} column density and only shows C\textsc{iv} and Si\textsc{iv} absorption at \(z \approx z_{\text{GRB}}\). The other exceptional system (GRB 050820) shows weak, broad N\textsubscript{v} absorption that is offset by \(\delta v \approx -100 \text{ km s}^{-1}\) from the peak optical depth of the low ions. These characteristics are fundamentally different compared to the remainder of the sample, and it suggests that more than one process is responsible for the production of N\textsubscript{v} gas along GRB sight lines. In the following, however, we will focus on the majority of the sample.

2.2. Comparisons with Other N\textsubscript{v} Surveys

The general characteristics of the GRB N\textsubscript{v} sample contrast with those for N\textsubscript{v} samples obtained from quasar sight lines through local and high-z galaxies. The most striking difference is the high detection rate of large N\textsuperscript{+4} column densities in GRB sight lines. Fox et al. (2007) have presented the results of a search for N\textsubscript{v} absorption in sight lines where they also surveyed the O\textsuperscript{+5} ion. They reported only two positive N\textsubscript{v} detections [each with \(N(\text{N}^{+4}) \approx 10^{13.5} \text{ cm}^{-2}\)] among six DLAs with both an O\textsc{v}i detection and N\textsubscript{v} coverage. They set upper limits to the N\textsuperscript{+4} column densities

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Collisional ionization equilibrium would imply \(T \gtrsim 10^5 \text{ K}\) and a Doppler parameter for the N gas of \(b \gtrsim 15 \text{ km s}^{-1}\). Line profile analysis of the echelle spectra indicate Doppler widths less than this value (e.g., M. Dessauges-Zavadsky et al. 2008, in preparation).
of $<10^{13}$ cm$^{-2}$ in the remainder of cases. Similarly, an inspection of the public Keck (HIRES+ESI) DLA database (Prochaska et al. 2007b) indicates that the incidence of N v detections to a column density limit of $10^{13}$ cm$^{-2}$ is less than 20% (see also A. J. Fox et al., in preparation). Therefore, the GRB sight lines show more frequent and much stronger N v absorption than random sight lines through high-$z$ galaxies. Regarding the local universe, the majority of sight lines through the Galactic halo and disk do exhibit N v absorption (Savage et al. 1997), but only a few ($\approx 10\%$) show column densities $N(N^{+4}) > 10^{14}$ cm$^{-2}$ and none have $N(N^{+4}) > 10^{14.5}$ cm$^{-2}$ (Indebetouw & Shull 2004b).

Another important difference is that the N v profiles for GRBs are kinematically "cold": they are narrow and have small offset (if any) from the low-ion line profiles. This contrasts with the majority of Galactic detections, whose N v line profiles are systematically broader than those for low ions. The Galactic N v lines have Doppler parameters ($b > 30$ km s$^{-1}$; Savage et al. 1997) that generally exceed those observed for the GRB data. By a similar token, very few Galactic N v profiles show peak optical depths $\tau_{1238} > 1$. In short, the profiles characteristic of GRB sight lines, i.e., narrow lines with large peak optical depths, are rarely observed in any astrophysical environment of the local universe. Regarding the N v detections in high-$z$ DLA galaxies, the few examples with positive N v detections are comprised of multiple components whose widths more resemble the GRB profiles. These examples, however, have much smaller peak optical depths than the majority of the GRB sample. Furthermore, these lines do not trace the peak optical depths of low-ion gas but are coincident with other high ions (e.g., C iv, O vi) often with offsets of several tens of kilometers per second from the low-ion features (Fox et al. 2007). The only extragalactic environment where narrow, strong N v profiles have been observed is in gas associated with quasars (e.g., D’Odorico et al. 2004). These associated systems are modeled as photoionized material at distances of a few tens of kiloparsecs from the QSO. In the following section, we will examine whether a similar process—photoionization by the GRB afterglow—explains our observations.

3. DISCUSSION

The observations presented in the previous section demonstrate the nearly ubiquitous detection of N$^{+4}$ gas at $z \approx z_{GRB}$ in GRB afterglow spectra. The N v absorption lines generally (1) have large peak optical depths with large integrated column densities $N(N^{+4}) \approx 10^{14}$ cm$^{-2}$; (2) have relatively narrow profiles ($<50$ km s$^{-1}$); (3) show small velocity offset from fine-structure and resonant low-ion absorption; and (4) exhibit no significant correlation with other physical characteristics (e.g., metallicity) of the nearby ISM. Similar to the fine-structure lines observed in GRB afterglow spectra (Prochaska et al. 2006), the prevalent detection of strong N v contrasts with sight lines through galaxies in the local and high-$z$ universe. Therefore, one infers that processes related to the GRB, its progenitor, and/or its host galaxy must produce the N$^{+4}$ gas. We will now explore possible origins of this gas and its implications for the GRB progenitor environment.

3.1. N v Arising in the Halo and Neutral ISM Gas

We begin by considering the galactic halo8 of the GRB host galaxy where one might expect a diffuse, hot baryonic component including N$^{+4}$ gas. This expectation stems from surveys of the Galactic halo where one observes a high covering fraction of high-ion gas including O vi and N v absorption (Sembach et al. 2003; Savage et al. 1997). The relative column densities of these ions, however, do not follow predictions from collisional ionization equilibrium (CIE) models, and researchers tend to invoke non-equilibrium scenarios to explain the observations (see Indebetouw & Shull 2004a for a recent review). These include turbulent mixing layers (Slavin et al. 1993), gas shocked by supernova remnants (Shull & McKee 1979), and conductive interfaces (Slavin & Cox 1992). None of these models describe all of the Galactic observations, and Indebetouw & Shull (2004b) have concluded that several (if not all) of the processes are likely to contribute. It is reasonable to consider whether these processes contribute to the N v absorption observed in GRB afterglow spectra. Several arguments point against this hypothesis. Regarding the theoretical models, none of the mechanisms introduced to explain Galactic N$^{+4}$ gas predict column densities significantly larger than $10^{13}$ cm$^{-2}$. In part, this may be because the models were computed to explain the Galactic data where one rarely finds N$^{+4}$ column densities as large as the GRB sample. Nevertheless, the models cannot reproduce the large N v optical depths unless one presumes a very large number of these layers and/or remnants. This "many absorber" scenario is challenged by the narrow N v profiles observed for the majority of GRB sight lines (Fig. 1), especially if one allows that the N abundance in GRB host galaxies is significantly subsolar (Prochaska et al. 2007a).

Furthermore, several lines of observational evidence challenge interpreting the N$^{+4}$ gas as galactic halo material. First, the GRB N v profiles have large optical depth, are more narrow, and are more tightly correlated with the neutral ISM than the N v profiles observed in the Galactic halo. Second, the coincidence of the N v and fine-structure profiles in velocity space suggests that the N$^{+4}$ gas occurs within $\approx 1$ kpc of the GRB. This is an indirect argument because N$^{+4}$ does not have its own fine-structure levels. Nevertheless, the coincidence in 4 of 5 sight lines showing N v absorption is statistical evidence that the N$^{+4}$ gas is located near the neutral phase. Note, however, that the difference in ionization potential between these ions means that the gas cannot be precisely coplanar. Third, and perhaps most important, the data support the presence of halo gas but not at the velocities of the N v absorption. Prochaska et al. (2008) have identified low column density features in strong Si ii and Fe ii transitions that do not exhibit corresponding Si ii or Fe ii absorption. Therefore, these "clouds" lie at distances greater than a few kiloparsecs from the GRB afterglow. The clouds tend to show corresponding high-ion absorption (Si iv, C iv) and have relative ion column densities suggestive of partially ionized gas. Prochaska et al. (2008) associate these clouds with the galactic halo. This halo gas does not exhibit N v absorption, and we infer that the clouds that do exhibit N$^{+4}$ gas are unrelated to the halo. Altogether, these theoretical and observational arguments disfavor a galactic halo origin for the majority of N$^{+4}$ gas observed in GRB sight lines. The only obvious exception is the weak, broad N v doublet observed toward GRB 050820, which is also significantly offset from the fine-structure absorption. We await larger GRB samples to assess the frequency of N v detections like this one.

Granted the small velocity offset observed between the N v profiles and the low-ion transitions, one should consider whether the gas is located near the neutral phase, i.e., within the ambient ISM of the galaxy. Indeed, observers have identified N$^{+4}$ gas in the Galactic ISM and even our Local Bubble (Savage et al. 1997; Welsh & Lallement 2005). Because N$^{+4}$ is not produced by even bright O stars, it must trace interstellar shocks from SNe, X-ray
emission from hot gas in the ISM, or gas near white dwarfs (e.g., Welsh & Lallement 2005; Dupree & Raymond 1983). In comparison with the GRB observations, however, the observed N^{+4} column densities of the Galactic ISM are generally small ($\lesssim 10^{13}$ cm$^{-2}$) and the line profiles are significantly broader. The values are even extreme for O vi gas in the Galactic ISM (Bowen et al. 2008), which always shows larger column densities than N vi gas. One counterexample is observed along the sight line to H1821+643 (Savage et al. 1995). In this case, one observes a strong N vi profile that is likely associated with the planetary nebula K1-16. At the redshifts of GRB host galaxies, however, planetary nebulae are rare or nonexistent, and we expect this process to have a negligible consequence. In summary, although we cannot unambiguously rule out the N vi gas arising in the ambient ISM, we consider this to be an unlikely scenario.

### 3.2. N vi Associated with the Starburst Phenomenon

Empirically, one observes N vi absorption in the individual and integrated spectra of $z \sim 3$ starburst galaxies (Lyman break galaxies [LBGs]; Pettini et al. 2002; Shapley et al. 2003). The VLT UVES spectrum of the lensed cb58 galaxy (Savaglio et al. 2002), for example, shows a strong N vi profile at a velocity consistent with other high-ion and low-ion (resonant and fine-structure) lines observed in the spectrum. All of this gas is offset by $\approx -200$ km s$^{-1}$ from the observed nebular emission lines, indicating a galactic-scale outflow, presumably associated with the current burst of star formation. The physical origin of N^{+4} has not been established for these high-z, starburst galaxies. Nevertheless, if GRB host galaxies are also driving galactic-scale winds (e.g., Thöne et al. 2007; Prochaska et al. 2008), then it is possible that the observed N vi absorption is related to this phenomenon. While these mechanisms deserve further attention, we note that the majority of GRB host galaxies are not massive starbursts but more resemble galaxies like NGC 1705, a local, poststarburst dwarf galaxy (Chen et al. 2007a). While a galaxy like NGC 1705 may also exhibit an outflow (Heckman & Leitherer 1997), the observed P Cygni N vi absorption is not associated with the galactic-scale outflow. In this respect, the N vi absorption associated with bright LBGs may not be relevant to the GRB afterglow spectrum.

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### 3.3. Do Stellar Winds Produce N vi Gas?

Massive stars are observed to generate stellar winds during the course of their main-sequence (MS) lifetimes and frequently during the stellar phases that follow. These stars are subject to severe mass loss throughout their lives; e.g., Galactic stars with initial masses above $\sim 25 M_\odot$ are thought to lose more than half of their initial mass before their final supernova explosions. Massive stars may pass through several phases having very different stellar winds during their evolution, which may produce a wide variety of structures in the surrounding gas. These stellar winds drive supersonic shock waves into the ambient gas, sweeping and heating it up. Under the presumption that GRB progenitors are massive stars, it is feasible that shocks produced by their stellar wind would produce an observable quantity of N vi gas.

The detailed dynamical evolution of the circumburst medium around massive stars is complex. Since massive stars pass through phases with very different mass-loss histories during their evolution, there will be a variety of structures in the surrounding gas. Indeed, at solar metallicities main-sequence stars of moderate mass (25–40 $M_\odot$) are thought to develop into red supergiants (RSGs) and thereafter Wolf-Rayet (WR) stars. The winds of possible GRB progenitors have been explored by a number of authors (Garcia-Segura et al. 1996; Ramirez-Ruiz et al. 2005; van Marle et al. 2005, 2008; Eldridge et al. 2006). These progenitor stars are thought to be the highly evolved descendants of main-sequence stars with initial masses larger than about 20 $M_\odot$.

In these models, there are up to three consecutive types of winds (see Fig. 2). The first is a rarefied, fast wind from the main-sequence star that sweeps up the ambient ISM, forming a main-sequence stellar wind bubble. Typical velocities are $v_{\text{rms}} \sim 10^3$ km s$^{-1}$, and mass-loss rates are $M \sim 10^{-6}$ to $10^{-7} M_\odot$ yr$^{-1}$, with lifetimes of $\tau_{\text{rms}} \sim 10^6$ yr (Herrero et al. 1992). A dense and slow wind follows as the star evolves to a RSG phase. This wind expands into the rarefied interior of the main-sequence bubble. This wind forms a dense, high-metallicity circumstellar medium surrounding the star. RSG wind strengths are $v_{\text{rms}} \sim 10$–25 km s$^{-1}$ and $M \sim 10^{-4}$ to $10^{-5} M_\odot$ yr$^{-1}$, with lifetimes of $\tau_{\text{rms}} \sim 10^5$ yr (Humphreys 1991). Finally, a fast wind from the WR phase with $v_{\text{rms}} \sim 10^3$ km s$^{-1}$ and $M \sim 10^{-5}$ to $10^{-6} M_\odot$ yr$^{-1}$ (Willis 1991), sweeps up the previous slow wind just prior to the death of the star. When the fast WR wind starts blowing, it sweeps up the RSG wind material into a shell, forming the observed WR ring nebula. Finally, the WR ring nebula breaks out of the RSG wind. After that, the hot...
shocked, WR wind expands into the remnant main-sequence bubble.

During the main-sequence phase, the stellar mass loss increases gradually, while the wind velocity decreases slightly, which results in an almost constant mechanical luminosity

\[ L_w = \frac{1}{2} M_w v_w^2. \] (1)

This behavior allows us to easily compute the time evolution of the main-sequence bubble using the analytical solutions given by Weaver et al. (1977). Their adiabatic thin-shell solutions are summarized as follows:

\[ E_{th} = \frac{5}{11} L_w t, \] (2)

\[ P_b = \frac{7}{(3850 \pi)^{2/5}} L_w^{2/5} \rho_0^{3/5} t^{-4/5}, \] (3)

\[ R_b = \left( \frac{125}{154 \pi} \right)^{1/5} L_w^{1/5} \rho_0^{-1/5} t^{4/5}, \] (4)

where \( E_{th} \) is the thermal energy of the hot shocked main-sequence gas, \( P_b \) is the thermal pressure of the shocked gas, \( R_b \) is the outer radius, and \( \rho_0 \) is the ISM constant density. These equations assume that the forward shock is completely radiative, whereas the hot bubble of the shocked wind material is adiabatic, which is a good approximation given that the hot shocked gas radiates poorly. The resulting shocked temperature can thus be estimated by

\[ T_{shocked} = \frac{3}{16} \frac{\mu m_H}{k} \Delta v_w^2 \sim 10^5 \left( \frac{\Delta v_w}{10^5 \text{ km s}^{-1}} \right)^2 \text{ K.} \] (5)

In addition, the above formalism assumes that the ISM is cold, so that it has no significant thermal pressure.

The approximation of a thin shell thus gives an estimate for the size of the circumstellar main-sequence bubble

\[ R_b = 52.9 \left( \frac{L_{ms}}{10^{36} \text{ ergs s}^{-1}} \right)^{1/5} \left( \frac{\rho_0}{10^{-23} \text{ g cm}^{-3}} \right)^{-1/5} \left( \frac{t_{ms}}{5 \times 10^9 \text{ yr}} \right)^{3/5} \text{ pc.} \] (6)

The wind termination shock at the end of the main-sequence phase is located at a radius \( R_{ms} \) such that the thermal pressure in the shocked wind material equals the hot bubble pressure. The posttermination shock pressure is roughly equal to the ram pressure in the wind, \( P_{ram} = \rho_{ms} v_{ms}^2 \), so that

\[ R_{ms} = 7.8 \left( \frac{M_{ms}}{10^{-6} M_\odot \text{ yr}^{-1}} \right)^{1/2} \left( \frac{v_{ms}}{10^3 \text{ km s}^{-1}} \right)^{1/2} \left( \frac{P_b}{3 \times 10^{-12} \text{ dyn cm}^{-2}} \right)^{-1/2} \text{ pc.} \] (7)

Eventually, the star leaves the main sequence and passes through the RSG phase. In the transition phase from main-sequence to RSG stage, the stellar wind increases its density and decreases its velocity. In total, the ram pressure is reduced (i.e., \( \rho_{ms} v_{ms}^2 \geq \rho_{sg} v_{sg}^2 \)), and the wind terminal shock loses its equilibrium position. It collapses and finds a new stationary location on the hydrodynamic timescale of the hot bubble. Once a new equilibrium point is found, a shell of shocked RSG wind starts to build up (although the RSG wind is slow, it is supersonic given its low temperature, which results in an extremely low sound speed). After the RSG phase, the star evolves directly to the WR phase. The fast wind sweeps up the previous slow RSG wind material into a shell. The value of \( L_w \) exceeds the mechanical luminosity of the RSG wind by several orders of magnitude, and as a result, the WR shell will eventually break out of the RSG wind. After that, the hot, shocked WR wind expands into the remnant main-sequence bubble.

To produce a detectable \( N \nu \) feature, the postshock temperature must be \( T_s \approx 10^4 \text{ K} \) to collisionally ionize nitrogen to \( N^{14} \) and the shock must extend beyond \( R \approx 20 \text{ pc} \) to avoid photoionization by the GRB afterglow (see the following section). These constraints rule out an RSG wind, as this is too weak to extend beyond a few parsecs. What is more, the RSG wind is ultimately heated and accelerated to large velocities by the WR wind before core collapse. Meanwhile, the speeds of MS and WR winds lead to a shock temperature \( T_s > 10^6 \text{ K} \) (e.g., van Marle et al. 2008). The only exception is in the dense shell of swept-up material at the wind’s edge, but this rapidly cools to \( \approx 10^4 \text{ K} \). Altogether, we conclude that stellar winds associated with the GRB progenitor will not lead to significant \( N \nu \) absorption.

In lieu of shocked gas from a single stellar wind, one could invoke shocks related to an expanding “superbubble,” perhaps associated with a starburst (e.g., Tenorio-Tagle et al. 1987). Following equation (5), the appropriate temperature for \( N \nu \) is achieved for an expansion speed of \( \approx 100 \text{ km s}^{-1} \). This simple scenario yields the following predictions for a shock-heated \( N \nu \) gas: the \( N \nu \) absorption will be offset by \( \delta v \approx -100 \text{ km s}^{-1} \) from the ISM gas and have a Doppler parameter consistent with \( T_s \approx 10^6 \text{ K} \) (i.e., \( b \approx 15 \text{ km s}^{-1} \)). Reviewing the GRB sight lines comprising our sample, GRB 050820 shows a surprisingly good match to these characteristics. Although other processes could explain the \( N \nu \) gas associated with this GRB (e.g., diffuse gas in the galactic halo), one may associate this \( N \nu \) detection with shocked gas. Conversely, the remainder of \( N \nu \) detections have small velocity offsets from the ISM and do not exhibit broad-line profiles characteristic of \( T_s \approx 10^5 \text{ K} \). For the majority of the GRB sample, therefore, we must consider an alternative process. Furthermore, the absence of \( N \nu \) detections at \( \delta v < 0 \text{ km s}^{-1} \) in these sight lines constrains the nature of stellar winds and the ISM. The data suggest that the stellar wind has a termination radius less than \( 10 \text{ pc} \) such that the afterglow has photoionized this material. We will explore this latter idea at greater length in the next section.

### 3.4. Photoionization by the Afterglow

In the previous sections we argued that the halo and neutral ISM of the host galaxy, as well as material shock heated by the progenitor’s stellar wind, are unlikely to yield \( N^{14} \) gas with characteristics resembling the majority of our GRB \( N \nu \) sample. Motivated by the narrow \( N \nu \) line profiles, we turn to a model where the \( N^{14} \) gas arises from photoionization. This cannot include ionization by an OB association because these stars emit too few photons at \( h\nu > 77 \text{ eV} \) to produce a meaningful column density of \( N^{14} \). Even a 40 \( M_\odot \) star emits too few photons during its lifetime to produce a significant \( N^{14} \) column density. The progenitor stars of GRBs, however, may be very massive stars that undergo a Wolf-Rayet phase with effective temperatures exceeding 100,000 K (Hirschi et al. 2005; Hammer et al. 2006). These could produce measurable column densities of \( N^{14} \), but

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\(^{10}\) Note that although rapidly rotating models suggest a higher flux of \( h\nu \approx 100 \text{ eV} \) photons (G. Meynet 2007, private communication), this will not change our conclusion.
only at distances \( r < \sim 1 \) pc from the WR star. We now demonstrate that this gas is photoionized by the GRB afterglow.

Owing to synchrotron processes, GRB afterglows have a roughly power-law spectrum with emission extending from the optical to X-ray frequencies. The afterglow, therefore, will initiate an ionization front, giving highly ionized material at small radii \((r < 1 \text{ pc})\) and progressively less ionized gas at larger radii as the photon flux decreases by \( r^{-2} \). The photon flux is sufficiently high that the \( r^{-2} \) dependence dominates over any attenuation (shielding) by the surrounding medium. One can estimate the distance where a specific ion (e.g., \( \text{N}^{+4} \)) will reach a maximum ionization fraction by comparing the photon flux \( f_\nu \), which ionizes the next lower ionization state (i.e., \( \text{N}^{+3} \)), against the photoionization cross section of that ion \([i.e., \sigma(\text{N}^{+3})]\). For \( f_\nu \sigma \ll 1 \), there will be a negligible ionization fraction. For \( f_\nu \sigma \gg 1 \), it is likely that the ion will be fully ionized to a higher state. The peak in the ionization fraction is therefore likely to occur where \( f_\nu \sigma \sim 1 \).

We can estimate this distance by adopting the afterglow of GRB 050730, which we parameterize as

\[
L_\nu = 7.4 \times 10^{50} \left( \frac{h \nu}{80 \text{ eV}} \right)^{-1.8} \left( \frac{t_{\text{obs}}}{100 \text{ s}} \right)^{-0.3} \text{ergs s}^{-1} \text{ Hz}^{-1}.
\]

Here the frequency \( \nu \) corresponds to the rest frame and \( t_{\text{obs}} \) is time in the observer frame. We integrate from \( t_{\text{obs}} = +10 \) s (i.e., we ignore effects associated with the prompt phase) to \( t_{\text{obs}} = +1000 \) s, which is a time typical for the onset of high-resolution spectroscopic observations. We calculate \( f_\nu \sigma = 3 \times 10^{35} \) photons emitted with energies in the interval \( 77 \text{ eV} < \nu < 95 \text{ eV} \), which bounds the ionization potentials of \( \text{N}^{+3} \) and \( \text{N}^{+4} \). At 1 pc, this implies a photon flux of \( f_\nu \sigma \equiv f_\nu (4\pi r^2) = 2.4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1} \), which exceeds the column density of N nuclei for \( n_{\text{H}} < 10^3 \text{ cm}^{-3} \) assuming a solar abundance (i.e., shielding is likely negligible). Finally, one compares the photon flux with the cross section of \( \text{N}^{+3} \), \( \sigma(\text{N}^{+3}) \). Using the parameterization of Verner et al. (1996)

\[
\sigma(\text{N}^{+3}) = 10^{-18} \text{ cm}^2 \text{ at } h \nu = 80 \text{ eV}.
\]

The distance where \( \text{N}^{+4} \) should reach a maximum value is roughly where the photon flux matches the cross section, i.e.,

\[
r_{\text{peak}} \approx \left[ \frac{\phi_\nu \sigma(\text{N}^{+3})}{4\pi} \right]^{1/2},
\]

or \( \approx 15 \) pc for our example.

We note that the spectral slope assumed here is steeper than most other afterglows and therefore implies a lower integrated photon luminosity at 100 eV than may be typical (some afterglows emit in excess of \( 10^{61} \) photons in the 77–95 eV interval).

Furthermore, we have ignored the prompt emission of \( \text{N}^{+4} \) ionizing photons. Adopting the spectral parameterization of the prompt X-ray emission observed for GRB 060614 as an example (Butler & Kocevski 2007), we estimate \( 10^{38} \) photons emitted during the prompt phase \( t_{\text{obs}} \leq 100 \) s. This low-redshift burst has a smaller X-ray luminosity than typical, and we estimate that the prompt phase can contribute in excess of \( 10^{40} \) photons. If \( E_{\text{peak}} \) evolves like \( r_{\text{peak}}^2 \) then to first order the prompt and afterglow phases will have comparable time-integrated photon fluxes at 100 eV.

To verify the distance estimate above and to explore a range of physical conditions, we have performed a series of time-dependent photoionization calculations for the propagation of ionizing flux through a constant-density medium (e.g., Perna & Lazzati 2002).

Our calculation follows the photons through a series of constant-density, optically thin layers allowing for absorption by H, He, C, N, and O. We ignore recombinations because the timescales exceed (by orders of magnitude) the duration of the observations. In the following, we have adopted the afterglow of GRB 050730 integrating from \( t_{\text{obs}} = +10 \) to +1000 s. In this respect, the calculation yields the ionization state of the gas that photons emitted at \( t_{\text{obs}} = +1000 \) s would "observe" as it traveled through the medium. [See the electronic edition of the Journal for a color version of this figure.]

The curves in Figure 3 show the ionization fractions of \( \text{N}^{+3} \), \( \text{N}^{+4} \), \( \text{He}^+ \), and \( \text{H}^0 \) as a function of distance from the GRB afterglow for \( n_{\text{H}} = 10^{-3} \) cm\(^{-3}\). We find that the majority of nitrogen gas at \( r_{\text{peak}} \approx 10 \) pc has been photoionized to \( \text{N}^{+4} \), while nitrogen gas at smaller distances is in higher ionization states and nitrogen gas at greater distances is in lower ionization states. The total \( \text{N}^{+4} \) column density predicted from this calculation (assuming \( n_{\text{H}} = 10^{-3} \) cm\(^{-3}\)) is

\[
N(\text{N}^{+4}) = 10^{14} \text{ cm}^{-2} \left[ \frac{(N/\text{H})}{10^{-6}} \right] \left[ n_{\text{H}} = 10 \text{ cm}^{-3} \right],
\]

where we note that \( (N/\text{H}) = 10^{-6} \) corresponds to 1/100 solar abundance. This calculation shows that even a modest density, subsolar gas can produce an \( \text{N}^{+4} \) column density consistent with the observations. We have repeated the calculations for a range of \( n_{\text{H}} \) values and find that the \( \text{N}^{+4} \) column density scales with \( n_{\text{H}} \) for small \( n_{\text{H}} \) values but has an approximately \( n_{\text{H}}^{1/2} \) dependence for \( n_{\text{H}} > 5 \) cm\(^{-3}\). The calculations also indicate that the \( \text{N}^{+4} \) ionic fraction peaks at a slightly smaller radius (by a few parsecs) for larger \( n_{\text{H}} \) but roughly the same position for smaller \( n_{\text{H}} \) values. These results are sensitive, however, to assumptions on the ionization state of the gas prior to the afterglow. Here we have assumed that the gas is neutral at \( t_{\text{obs}} = 10 \) s at all radii \( r > 1 \) pc. If one allows for a preexisting \( \text{H}^0 \) region extending to greater than 30 pc (e.g., Whalen et al. 2008), this gives more \( \text{N}^{+4} \) gas at larger radii and a larger total \( \text{N}^{+4} \) column density due to reduced shielding by \( \text{H}^0 \) gas, but the differences are modest (<30%). We have also explored afterglows with a range of luminosities. This is identical to studying a single system at various times \( t_{\text{obs}} \).
because the only relevant quantity is the integrated photon flux prior to the time of observation. Not surprisingly, both $t_{\text{peak}}$ and the integrated N$^4$ column densities increase with the afterglow luminosity (Fig. 4).

The results presented in Figure 3 and described above reveal a generic prediction for GRB afterglows. Just as the $\approx 6$ eV far-UV photons excite Si$^+$ and Fe$^+$ ions out to 1 kpc distance, the $\approx 80$ eV photons from the afterglow photoionize nearly all nitrogen at $r \approx 10$ pc to N$^4$. Furthermore, the strengths of the N $\nu$ absorption should not be correlated with H $i$ column density and will at best be loosely correlated with the low-ion column density. These predictions are consistent with the current sample of observations. The photoionization scenario described here will also imply significant absorption by other high ions, e.g., C $\nu$, O $\nu$ transitions. Figure 1 shows that we observed strong C $\nu$ absorption at the velocity of N $\nu$ in every case. We find, however, that the signal-to-noise ratio and line blending in the current spectra prohibit a meaningful search for the O $\nu$ doublet. In summary, we predict detectable N $\nu$ absorption in all GRB afterglow spectra except where the gas at $r \approx 10$ pc has very low nitrogen density $n_{N} \equiv n_{\text{H}}(N/H)$ or has been collisionally ionized to higher states (i.e., $T > 10^6$ K).

A high-temperature ($T > 10^6$ K; shocked wind) and low density gas is in fact predicted at $r \approx 10$ pc in the stellar winds of GRB progenitors (e.g., van Marle et al. 2005). If we are to explain narrow N $\nu$ absorption with small velocity offset from the neutral gas, one must conclude that the stellar wind does not extend beyond $r \approx 10$ pc. Referring to equation (6), this implies

$$\rho_{0} \gtrsim 8 \times 10^{-20} \left( \frac{L_{\text{ms}}}{10^{36} \text{ ergs s}^{-1}} \right) \left( \frac{t_{\text{ms}}}{5 \times 10^{6} \text{ yr}} \right)^{3} \text{ g cm}^{-3}. \quad (11)$$

This restriction is, however, only valid if the ISM is cold so that the circumstellar bubble expands supersonically with respect to the surrounding ISM. For a sufficiently high ISM temperature, the thermal pressure of the ISM will act as an extra confining force. An example of this is an H $\nu$ region. In such an environment, the main-sequence wind can never create a supersonically expanding shell. Pressure balance between the thermal pressure in the hot wind bubble and the thermal pressure of the ISM (with $n_0$ particle density)

$$P_{0} = 10^{-10} \left( \frac{n_0}{1 \text{ cm}^{-3}} \right) \left( \frac{T}{10^6 \text{ K}} \right) \text{ dyn cm}^{-2} \quad (12)$$

gives the radius of the wind termination shock

$$R_{\text{ms}} = 1.2 \left( \frac{M_{\text{ms}}}{10^{-6} M_{\odot} \text{ yr}^{-1}} \right)^{1/2} \left( \frac{v_{\text{ms}}}{10^{-1} \text{ km s}^{-1}} \right)^{1/2} \left( \frac{P_{0}}{10^{-10} \text{ dyn cm}^{-2}} \right)^{-1/2} \text{ pc.} \quad (13)$$

Another scenario that would avoid the complications due to a steady stellar wind is a progenitor system that moves rapidly through the interstellar medium (e.g., Hammer et al. 2006; van Marle et al. 2006). A complementary conclusion can be drawn from this analysis: GRB progenitor models that predict stellar winds extending beyond 10 pc must invoke a new process to explain the strong, narrow N $\nu$ profiles with small offset observed for the majority of GRB sight lines.

These issues suggest an additional problem: Where is the gas related to afterglow photoionization in GRB 050820 for which one only observes relatively weak, broad N $\nu$ absorption offset by $\delta v \approx -100$ km s$^{-1}$ from the low-ion gas? In the previous section, we suggested that the N $\nu$ gas for GRB 050820 may be explained by shock-heated gas associated with an expanding superbubble. Provided this bubble extends beyond 10 pc, the material photoionized by the afterglow will occur at $\delta v < 0$ km s$^{-1}$. Furthermore, this gas is likely to have temperatures that ionize N beyond N$^4$.

Adopting the afterglow photoionization model, we can use the observed N$^4$ column density to constrain $n_\text{N}$ at $r \approx 10$ pc from the afterglow. Let us consider a few examples from the current sample under the assumption that the afterglow ionization scenario is the only mechanism relevant to N$^4$ production. For those sight lines with $N(N^4) > 10^{14}$ cm$^{-2}$, we derive this constraint: $\log(n_{\text{H}}/\text{cm}^{-3}) + [N/H] \gtrsim -1$ dex. This is a relatively modest density and enrichment level; if GRB progenitors arise in star-forming regions, one may expect these conditions to be satisfied for nearly every GRB. The nondetection of N$^4$ gas toward GRB 060607, therefore, has a surprising implication. The upper limit of $N(N^4) < 10^{12.6}$ cm$^{-2}$ gives $\log(n_{\text{H}}/\text{cm}^{-3}) + [N/H] < -2.7$ dex. This observation suggests both a metal-poor gas and a low-density medium surrounding the GRB. It is interesting to note that this GRB also shows the lowest H $i$ column density of any GRB sight line to date (Chen et al. 2007b). This may indicate that some GRB events occur outside of both their star-forming regions and the ISM of the host galaxy.

If one allows that the metalliclicity of the neutral ISM (inferred from low-ion transitions) is applicable for the gas near the GRB, then one can constrain the $n_{\text{H}}$ density alone. In a few cases (050730, 050820, 050922C), one observes N $\nu$ transitions and can constrain N/H directly (Prochaska et al. 2007a). For example, the afterglow spectrum of GRB 050922C shows $|N/H| < -4$ and $N(N^4) > 10^{14.2}$ cm$^{-2}$. This implies $n_{\text{H}} > 10^3$ cm$^{-3}$ unless one assumes that the gas is enriched in N local to the GRB (M. Dessauges-Zavadsky et al. 2008, in preparation). We note that this density is comparable to the value needed to confine a stellar wind to $r < 10$ pc (see above). A summary of the constraints on the physical conditions for our data set is given in Table 3.
Ultimately, the most valuable constraints may come from a time series of spectroscopy (e.g., Vreeswijk et al. 2007) to investigate variability in the kinematics. Figure 4 indicates that $t_{\text{peak}}$ increases by factors of a few during the first 1000 s of the afterglow. Therefore, one would be sensitive to the kinematics of the gas at a range of radii allowing constraints on the differential motions at these distances. We have searched for temporal variations in the strength and velocity of the N v gas in the Keck HIRES spectrum of GRB 050820 (two exposures of 900 s starting at $t_{\text{obs}} \approx 3300$ s) and the Magellan MIKE spectrum of GRB 050730 (three 1800 s exposures starting at $t_{\text{obs}} \approx 4$ hr; Prochaska et al. 2007c). The N v equivalent widths and line centroids are not observed to vary with statistical significance. We set upper limits of $\Delta W < 25$ mÅ and $\Delta v = 10 \text{ km s}^{-1}$ based on these modest S/N spectra.

### 4. CONCLUDING REMARKS

We have performed a survey of N v absorption along seven GRB sight lines and reported six positive detections within 100 km s$^{-1}$ of the neutral gas associated with the host galaxy. Aside from the GRB 050820 sight line (where the N v absorption is broad, weak, and offset by $\delta v \approx -100 \text{ km s}^{-1}$), the N$^{14}$ gas has large column density and kinematically “cold” line profiles. The latter characteristic refers to a low velocity dispersion and a small offset $|\delta v| < 20 \text{ km s}^{-1}$ from the neutral gas. The N v profiles are also coincident in velocity with fine-structure absorption, which suggests that the gas is located within $\approx 1$ kpc of the GRB afterglow.

We have explored several scenarios that could produce N v absorption along GRB sight lines. Models related to the halo of the host galaxy or material shock heated by the progenitor’s stellar wind are disfavored by the observations. In contrast, a scenario where the N$^{14}$ gas is material photoionized by the GRB afterglow naturally reproduces the observations provided the gas at $r \approx 10$ pc is cold ($T \approx 10^4$ K) and has a modest density ($n \approx 1 \text{ cm}^{-3}$), a nonnegligible metallicity ([N/H] > -2), and a similar velocity as the ISM at $r \approx 100$ pc.

The afterglow photoionization model places several important constraints on the progenitor and its environment. In particular, this scenario requires that the stellar wind of the progenitor terminates at less than $r \approx 10$ pc. This suggests that the GRB progenitor has a weak, main-sequence stellar wind owing to a low mass-loss rate, a low wind speed, and/or a short lifetime. These characteristics may be a natural consequence of the progenitors that favor the GRB phenomenon, e.g., higher mass, lower metallicity stars. The wind can also be confined by introducing a dense ($n \approx 10^3 \text{ cm}^{-3}$) external medium. Perhaps GRBs are preferentially embedded within the dense regions of molecular clouds as opposed to a violent, starburst region. On the other hand, we note that the N v absorption detected along the GRB 050820 sight line has characteristics consistent with shock-heated gas provided a shock with $v \approx 100 \text{ km s}^{-1}$. In this case, we may be seeing the signatures of a starburst galaxy.

Before concluding, we wish to comment on a few directions for future research. One aspect to explore is how the soft X-ray absorption observed in the afterglow spectroscopy compares with the N$^{14}$ observations. To zeroth order, both measurements are sensitive to the column density of metals near the GRB progenitor, although likely at somewhat different radii. A comprehensive model of these observations may constrain the density profile of gas close to the GRB. Another implication of our research is that one predicts recombinations of the N$^{14}$ gas (and other high ions, e.g., O$^{15}$) once the afterglow fades. For low-z GRBs, it may be possible to observe this line emission with a sensitive ultraviolet telescope (Perna et al. 2000). Finally, one predicts that other high ionization states will be produced by the afterglow (e.g., O$^{15}$, S$^{15}$) that could be studied in a similar fashion to constrain the relative abundances of gas near the progenitor star.

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### TABLE 3

| GRB              | [N/H]$^a$ | log (nH/cm$^{-3}$)$^a$ |
|------------------|-----------|------------------------|
| GRB 021004       | -3.0      | 2.3                    |
| GRB 030323       | -1.9      | <0.9                   |
| GRB 050730       | -3.2      | 1.9                    |
| GRB 050820       | >-1.3     | <0.5                   |
| GRB 050922C      | <-4.1     | >3.0                   |
| GRB 060206       | -1.9      | 0.3                    |
| GRB 060607       | -2.0      | <-0.7                 |

$^a$ Nitrogen metallicity inferred from the ratio of N$^0$ and H$^0$ column densities (Prochaska et al. 2007a). This gas is located at a distance of 100 pc to a few kpc from the GRB afterglow. Systems marked with an asterisk do not have N v observations and we have set [N/H] = [M/H] = 1.

$^b$ Scaled from our photoionization models assuming the afterglow (GRB 050730) used throughout the paper.
