SUPER STAR CLUSTER NGC 1705-1: A LOCAL ANALOG TO THE BIRTH SITE OF LONG-DURATION $\gamma$-RAY BURSTS

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ABSTRACT

Recent observations suggest that global properties of the host galaxies for long-duration $\gamma$-ray bursts (GRBs) are particularly well suited for creating the massive star progenitors of these GRBs. Motivated by the hypothesis that massive young star clusters located in metal-poor, low-metallicity galaxies are a natural birth site for GRB progenitors, we present a comparison study of the ISM properties along the sight line toward the super star cluster NGC 1705-1 and those in distant GRB hosts. Using the same set of metal transitions in the UV and applying known ISM structures in NGC 1705, we find that NGC 1705-1 resembles distant GRB host galaxies in its high neutral gas column, low molecular gas fraction, low metallicity, $\alpha$-element enhancement, and low dust depletion. The lack of molecular gas is due to the enhanced UV radiation field in the starburst environment, consistent with the expectations for GRB progenitors. In addition, the known presence of dense neutral gas clouds at $r \leq 500$ pc from NGC 1705-1 provides a natural reservoir of C$^+$, Si$^+$, and Fe$^+$ ions that may be subsequently excited by the afterglow UV radiation field to produce excited lines commonly seen in GRB host ISM. We further argue that the apparent offset in the velocity profiles of low- and high-ionization transitions from absorption-line observations alone already offers important clues for related starburst episodes in GRB host galaxies. Our study shows that a statistical comparison between the ISM around star clusters and high-redshift GRB progenitors is important for identifying the key physical parameters that facilitate the formation of GRBs.

Subject headings: gamma rays: bursts — intergalactic medium — ISM: abundances — ISM: kinematics and dynamics

Online material: color figure

1. INTRODUCTION

Mounting evidence has lent strong support for the origin of long-duration $\gamma$-ray bursts (GRBs) in the death of massive stars (see Woosley & Bloom 2006 for a review; but also see Fynbo et al. [2006a], Gal-Yam et al. [2006], and Della Valle et al. [2006] for recent discoveries). Specifically, a direct association between GRBs and Type Ib/c supernovae (SNe) is established for GRBs 980425, 030329, and 031203 (Patat et al. 2001; Hjorth et al. 2003; Stanek et al. 2003; Malesani et al. 2004). These SNe of Type Ic show no hydrogen or strong Si$^+$ transitions in their spectra and have never been seen in elliptical galaxies (Filippenko 1997). While it is conceivable that all long-duration GRBs occur contemporaneously with a Type Ic SN, their low event rate indicates that only a small fraction ($<0.1\%$) of Type Ic SNe are accompanied by a GRB phase (van Putten 2004; Podsiadlowski et al. 2004; Soderberg et al. 2006). For stars to lose their hydrogen envelope prior to the core collapse and form a GRB, current theoretical models have hived on progenitors with initial stellar mass of $M = 25-30 M_\odot$, fast rotation speed, and low metallicity $Z \lesssim 10\% Z_\odot$ (Woosley & Heger 2006).

These GRBs are therefore expected to originate preferentially in metal-poor environment and/or underluminous galaxies. Observations of five nearby ($z_{GRB} < 0.17$) host galaxies indeed show that the host galaxies tend to be underluminous and that two of these galaxies also have an integrated H II region abundance below what is expected from a nominal luminosity-metallicity relation of field galaxies (e.g., Prochaska et al. 2004; Modjaz et al. 2007). At the same time, chemical abundance studies of high-redshift ($z > 1$) hosts have been carried out based on absorption lines identified in early-time afterglow spectra (e.g., Fynbo et al. 2006b; Savaglio 2006; Prochaska et al. 2007), where the emission lines of an H II region become too faint to be detected. Abundance measurements of the cold interstellar medium (ISM) based on absorption-line studies, despite representing only a small volume along a pencil beam from the afterglow, are less subject to uncertainties in the ionization fraction or temperature of the gas and therefore offer a more accurate assessment of the metallicity. Comprehensive studies of afterglow absorption-line spectra have also allowed us to resolve gas at $\sim 100$ pc from the progenitor stars, providing direct constraints on the ISM properties of the progenitor environment (e.g., Prochaska et al. 2006; Chen et al. 2007; Vreeswijk et al. 2007).

However, our understanding of the progenitor environment is far from clear. For example, roughly 50% of GRB afterglows are located behind a large column of neutral gas with log $N(H i) = 21.5-22.5$ (Jakobsson et al. 2006) but no trace of molecular gas to very low limits $f_{H_2} = 2(N(H_2)/[N(H i) + 2N(H_2)]) \lesssim 10^{-6}$ (Tumlinson et al. 2007). Using a sample of 16 afterglow spectra, Prochaska et al. (2007) showed that GRB hosts have subsolar chemical abundances and an $\alpha$-element enhancement relative to Fe in the ISM, but also that a nonnegligible fraction exhibit $>10\%$ solar abundances. These authors also showed that even with a large neutral gas column, there can be little dust extinction along the sight lines in the host ISM toward the afterglows (see also Starling et al. 2007). The lack of $H_2$ can, in principle, be explained by a high destruction rate due to the enhanced photoionization radiation field in the star-forming cloud that hosts the GRB progenitor and by a low formation rate inferred from the observed
low metallicity. But at high enough gas density ($n_H > 10^3$ cm$^{-3}$), self-shielding is expected to be effective and will promote H$_2$ survival (e.g., Tumlinson et al. 2007).

Super star clusters provide an interesting local analog for understanding the formation of GRBs for two main reasons. First, Wolf-Rayet stars, popular candidates for GRB progenitors (e.g., Woosley & Bloom 2006), are often found in young star clusters (see Crowther 2007 for references). Second, star clusters contain a large number of massive stars in a small volume and are expected to have on average a higher rate of stellar collision and mass transfer between individual stars for nurturing the formation of a GRB. Various authors have proposed that dense stellar environments facilitate stellar coalescence for forming black holes that power the GRBs (e.g., Hansen & Murali 1998; Efremov 2001). In addition, GRBs have been considered a possible source for powering giant H$_2$ superbubble shells found in nearby galaxies (Efremov et al. 1999; Loeb & Perna 1998). A direct comparison between absorption-line properties in the ISM surrounding super star clusters and those identified in GRB host galaxies may therefore provide important calibrations for interpreting afterglow absorption-line observations.

To gain further insights for interpreting the afterglow absorption-line spectra of high-redshift GRBs, we have searched for ultraviolet echelle spectra of nearby super star clusters in the *Hubble Space Telescope* (HST) Data Archive. NGC 1705-1, a super star cluster located at the center of a blue compact dwarf galaxy NGC 1705 at redshift $z = 0.002$, is the only star cluster with high-quality echelle spectra from the Space Telescope Imaging Spectrograph (STIS). The galaxy is a well-known starburst galaxy that exhibits evidence of galactic scale gas outflows. It has a total luminosity of $\sim 0.01L_\odot$, and an H II region abundance of $\approx 35\%$ solar (e.g., Lee & Skillman 2004). A comparison between the ongoing star formation rate and B-band luminosity indicates a formation timescale that is much shorter than normal irregular galaxies and comparable to what is known for GRB host galaxies at high redshift (e.g., Christensen et al. 2004). The spectra of the super star cluster were originally taken for studying the physical conditions of the galactic winds driven by starburst outflows (see, e.g., Vázquez et al. 2004). Here we revisit this data set and present new column density measurements of various low-ionization species. We compare the ISM properties of the dense star cluster with those of high-redshift GRB host galaxies.

This paper is organized as follows. In § 2, we review known ISM properties integrated over the entire galaxy NGC 1705 and ISM properties that are local to the super star cluster NGC 1705-1. In § 3, we present our absorption-line measurements of the cold gas along the line of sight toward NGC 1705-1. In § 4, we compare the ISM properties of NGC 1705-1 with measurements for high-redshift GRB hosts. We describe the value of collecting echelle spectra of nearby super star clusters using future space UV facilities, such as the Cosmic Origin Spectrograph, for understanding the GRB progenitor environment at high redshift.

2. REVIEW OF NGC 1705

NGC 1705 is a well-known starburst galaxy at $z = 0.00209$ that has been studied extensively over a broad spectral window, from ultraviolet through radio frequencies (e.g., Lamb et al. 1985; Calzetti et al. 1994; Meurer et al. 1998; Lee & Skillman 2004). This blue irregular galaxy hosts a super star cluster, NGC 1705-1 (Fig. 1), which is among the brightest star clusters in the local universe and contributes roughly 40% of the total UV light of the galaxy (Meurer et al. 1992). Spatially resolved strong emission lines indicate that the warm ISM in the H I region can be characterized with an electron temperature of $T_e = (1.1-2) \times 10^4$ K (Lee & Skillman 2004). One of the most notable features in the ISM of NGC 1705 is the multiple superbubble shells, indicating gas outflow driven by the last episode of starburst, roughly $10^7$ yr ago that also formed most of the stars (\sim $10^5 M_\odot$) seen today in NGC 1705-1 (Meurer et al. 1992). The galaxy also exhibits very little intrinsic reddening (Calzetti et al. 1994) and shows no sign of molecular gas to very sensitive levels (Greve et al. 1996; Hoopes et al. 2004).

Moderate- to high-resolution UV spectra of NGC 1705-1 from different space facilities are published in the literature. While most of the absorption lines identified in the spectra are of ISM origin (York et al. 1990), detailed stellar population analysis based on a few stellar photospheric lines have placed strong constraints on the age, metallicity, and IMF of the cluster (Vázquez et al. 2004). The ISM absorption lines exhibit two strong components with respective blueshifted velocity of $v \approx -43$ and $-77$ km s$^{-1}$ (Heckman et al. 2001; Vázquez et al. 2004). The low-velocity component is believed to trace the cold, neutral ISM, while the high-velocity component is interpreted to originate in a gas outflow. Abundance measurements based on low-ionization species such as N$^+$, S$^+$, and Fe$^+$ support the scenario that the cold neutral ISM has been enriched primarily by Type II SNe that occurred in the star cluster roughly $10^7$ yr ago (Sahu & Blades 1997; Sahu 1998). In addition, the observed kinematic profile and the absorption strength of the O iv doublet are consistent with the expectations of supernovae undergoing radiative cooling (Heckman et al. 2001).

A summary of the known properties of galaxy NGC 1705 and the super star cluster NGC 1705-1 is presented in Table 1. We note that ISM absorption-line measurements in the table are based primarily on previous *Far-Ultraviolet Spectroscopic Explorer* (FUSE) observations (e.g., Heckman et al. 2001; Hoopes et al. 2004).

3. ISM PROPERTIES OF NGC 1705-1

3.1. STIS Echelle Spectra

We have retrieved all available STIS echelle spectra of NGC 1705-1 in the *HST* Data Archive. The observations were carried out using a $0.2'' \times 0.2''$ slit and three different grating setups for a total exposure time of 28,569 s (PID: 8297). Individual echelle spectra were reduced, extracted, and calibrated using standard pipeline techniques. To form a final spectrum for absorption-line studies, we calculated a weighted average of individual spectra and the corresponding 1 $\sigma$ error array per grating setup, with the weighting factor determined by the inverse variance. We normalized the mean spectrum with a best-fit, low-order polynomial continuum. The combined and normalized spectra have a spectral resolution of $FWHM \approx 7$ km s$^{-1}$, covering wavelength ranges $\lambda = 1150-1708$ Å with the E140M grating at signal-to-noise ratio S/N $\approx 12$ and $\lambda = 1700-3060$ Å with the E230M grating at S/N $\approx 7$ per resolution element.

3.2. Column Density Measurements

Absorption lines of heavy ions identified in the ISM of NGC 1705 exhibit complex absorption profiles. In Figure 2, we present in the three left panels low-ionization species and in the right column high-ionization species. The zero relative velocity ($v_{rel} = 0$) corresponds to the systemic redshift of NGC 1705 $z = 0.00209$, measured in H I 21 cm (Meurer et al. 1992) and in stellar photospheric transitions (Vázquez et al. 2004). The spectra include absorption features from the Milky Way and a foreground high-velocity cloud (Sahu & Blades 1997), which occasionally blend
with features from NGC 1705. These contaminating features have been identified and are indicated with dotted lines in the panels. In addition, stellar photospheric features are apparent in transitions such as C iv and Si iv, as a broad, shallow component extending from \( v = -500 \) through \( 300 \) km s\(^{-1}\).

The low- and high-ionization species in the ISM of NGC 1705 exhibit distinct kinematic signatures. The low-ionization resonance lines (which exclude the excited C\(^+\) transition, C\(^{+}\) 1335), show two narrow components, at \( v = -20 \) and \( -40 \) km s\(^{-1}\), while the high-ionization elements are broad and show velocity centroids systematically blueshifted to \( v = -70 \) km s\(^{-1}\). These high-ionization species share the same kinematic feature as the O iv absorption doublet discussed in Heckman et al. (2001).

We measure the column density of each ion using the apparent optical depth method (Savage & Sembach 1991) over a velocity interval of \( v = -100 \) to \(+40 \) km s\(^{-1}\) for low-ionization transitions and \( v = -250 \) to \(+100 \) km s\(^{-1}\) for high-ionization transitions. One exception is the S \( \text{ii} \) \( \lambda 1259 \) transition, where the line is contaminated by the Si \( \text{ii} \) \( \lambda 1260 \) transition from the foreground high-velocity cloud. We determine \( N(S \text{ ii}) \) using the VPFIT software package, including multiple components. The measurements are summarized in Table 2.

The H\(^i\) Ly\(\alpha\) transition of NGC 1705 is present in the STIS spectrum. It is saturated and blended with absorption from the Milky Way (Fig. 3). We note, however, that the \( N(H \text{ i}) \) value of NGC 1705 is well constrained by the red damping wing. We have performed a Voigt profile analysis and found \( \log N(H \text{ i}) = 20.05 \pm 0.15 \) for NGC 1705 and \( \log N(H \text{ i}) = 19.7 \) for the Milky Way. This is consistent with the finding of Sahu (1998) and Heckman et al. (2001) based on HST GHRS and FUSE observations, respectively. The best-fit model profile combining absorption from the Milky Way and NGC 1705 is presented as the red curve in Figure 3. The total H\(^i\) gas column density observed along the sight line toward NGC 1705-1 is only about 10% of what is observed in H\(^i\) 21 cm emission (Meurer et al. 1992), indicating that the super cluster is located near the front edge of the galaxy and that the sight line only probes a fraction of the (presumably outer) gaseous disk.

### 3.3. Chemical Composition of the Cold ISM

Based on the column density measurements presented in Table 2, we derive an iron abundance of \( [\text{Fe}/H] = -1.1 \pm 0.2 \) and a sulfur abundance of \( [\text{S}/H] = -0.6 \pm 0.1 \) with respect to the solar values from Asplund et al. (2005). The sulfur abundance in the...
The lack of excited C\(^+\) in the neutral gas implies a warm neutral medium and/or low dust content (Wolfe et al. 2003).

3.4. Gas Density and Temperature of the Ionized Gas

As noted earlier, high-ionization transitions such as C\(^{\text{iv}}\) \(\lambda\lambda\lambda 1548, 1550, \text{Si}\,\text{iii}\,\lambda\lambda\lambda 1206, \text{Si}\,\text{iv}\,\lambda\lambda\lambda 1393, 1402, \text{and Al}\,\text{ii}\,\lambda\lambda\lambda 1854, 1862\) are observed to be blueshifted at \(v \approx -77\,\text{km}\,\text{s}\^{-1}\) in the STIS echelle spectra (Fig. 2). These coincide in velocity space with the O\(^{\text{iv}}\) absorption doublet reported by Heckman et al. (2001). In particular, we note the presence of strong C\(^+\) at the same velocity offset, where little Fe\(^{\text{ii}}\) absorption has been detected. This is similar to what is observed in the ISM toward HD 192639 (Sonnenstrucker et al. 2002), whose origin is interpreted to be in shocks produced by expanding superbubble shells or stellar winds.

The broad line widths seen in unsaturated lines such as C\(^{\text{ii}}\) \(\lambda\lambda\lambda 1335\) and Al\(^{\text{ii}}\) \(\lambda\lambda\lambda 1854\) are suggestive of a collisional ionization origin. Adopting the observed S\(^{\text{iii}}\) and S\(^{\text{iv}}\) transitions that share the same kinematic features with the O\(^{\text{iv}}\) absorber (Heckman et al. 2001), we find \(\log N(\text{S}\,\text{iii}) - \log N(\text{S}\,\text{iv}) < 0.57\) and constrain the gas temperature at \(T > 6 \times 10^4\,\text{K}\) under a collisional ionization equilibrium. Further constraints for the gas temperature can be obtained by comparing the line width of C\(^{\text{ii}}\) \(\lambda\lambda\lambda 1335\) and Al\(^{\text{ii}}\) \(\lambda\lambda\lambda 1854\). We measure a Doppler parameter of \(b_{\text{c}} = 22.5 \pm 1.2\,\text{km}\,\text{s}\^{-1}\) for C\(^{\text{ii}}\) and \(b_{\text{Al\,\text{ii}}} = 17.73 \pm 5.4\,\text{km}\,\text{s}\^{-1}\) for Al\(^{\text{ii}}\) from the STIS spectra. Assuming that these ions originate at the same location, we further infer a gas temperature of \(T \approx 2.5 \times 10^5\,\text{K}\) and a turbulent velocity of \(b_0 \approx 12.6\,\text{km}\,\text{s}\^{-1}\).

Under a collisional excitation scenario, we can also constrain the density of ionized gas based on the relative strengths of the resonance absorption and the absorption from excited states. Given that the C\(^{\text{ii}}\) \(\lambda\lambda\lambda 1334\) transition is fully saturated, we obtain the constraint using the relative abundance of the excited Si\(^{\text{i}}\) and the ground-state Si\(^{\text{ii}}\). The high-velocity component at \(v \approx -77\,\text{km}\,\text{s}\^{-1}\) is moderately resolved from the warm- and cold-gas components. We perform a multiple-component Voigt profile analysis and measure \(\log N(\text{Si}\,\text{ii}) = 13.8 \pm 0.1\) and \(b = 8.7 \pm 0.9\,\text{km}\,\text{s}\^{-1}\) for the high-velocity component. The lack of Si\(^{\text{ii}}\) yields \(N(\text{Si}\,\text{ii}^+) / N(\text{Si}\,\text{ii}) < 0.04\), leading to an electron density \(n_e \approx 50\,\text{cm}^{-3}\) for \(T_e \sim 10^5\,\text{K}\).

4. DISCUSSION

Recent observations of GRB host environments have yielded two main results. First, the ISM of long-duration GRBs appear to be essentially devoid of molecular gas, despite exhibiting strong neutral hydrogen absorption columns. Second, these GRBs occur preferentially in metal-poor, low-metallicity, low-luminosity, actively star-forming galaxies. Together these suggest that global properties of the hosts are particularly well suited for the creation of the massive star progenitors thought to give rise to GRBs. If true, the study of local analogs of the sorts of environments amenable to GRB progenitor birth should help in understanding the nature of distant GRB birth sites.

NGC 1705 is a well-known starburst galaxy in the nearby universe, of special interest because of the clear presence of substantial O\(^{\text{ii+}}\) in a starburst-driven outflow. We have revisited and presented new measurements of the ISM properties along the line of sight toward the super star cluster NGC 1705-1, using archived but unanalyzed STIS echelle spectra. The study is motivated by the hypothesis that massive young star clusters offer a birth site for the progenitor stars of high-redshift GRBs, because of the dense stellar environment (e.g., Hansen & Murali 1998; Efremov 2001). The available STIS UV echelle spectra of the cluster show numerous ionic transitions with a complex velocity structure and allow us to use the same set of metal absorption lines for a direct

| Table 1 |
|---------------------------------|
| **Summary of Previously Derived Stellar and ISM Properties** |
| Property | Measurement | References |
|---|---|---|
| Galaxy NGC 1705 | | |
| Distance (Mpc) | 5.1 \pm 0.6 | 1 |
| \(M_\odot\) | -15.6 \pm 0.2 | 2 |
| Star formation rate (\(M_\odot\) yr\(^{-1}\)) | 0.06 | 3 |
| Formation timescale (\(T_\phi = L_\text{FR}/\text{SFR Gyr}\)) | 4.3 | 3 |
| The Star Cluster NGC 1705-1 | | |
| Stellar mass \((10^6 M_\odot)\) | (4.8 \pm 1.2) | 4 |
| Effective radius (pc) | 1.6 \pm 0.4 | 4 |
| Age (Myr) | 12.3 \pm 5 | 5 |
| \(H\,\text{ii}\) region 12 + \log(O/H) | 8.21 \pm 0.05 | 3 |
| \(H\,\text{ii}\) region 12 + \log(N/H) | 6.46 \pm 0.08 | 3 |
| \(T_e (10^4 \text{K})\) | 1.1 - 2 | 3 |
| \(E(B-V)\) | \leq 0.02 mag | 6 |
| The Neutral ISM | | |
| \(v (\text{km s}^{-1})\) | -43 | 5 |
| \(N(\text{H}\,\text{ii}) \text{ (cm}^{-2}\) | \(<3.9 \times 10^{14}\) | 7 |
| \(N(\text{H}\,\text{ii}) \text{ (cm}^{-2}\) (21 cm) | \((1-2) \times 10^{21}\) | 8 |
| \(\log N(\text{H}\,\text{ii}) \text{ (Ly}\beta\text{ absorption)}\) | 20.2 \pm 0.2 | 9 |
| \(\log N(\text{O}\,\text{ii})\) | 15.63 \pm 0.08 | 9a |
| \(\log N(\text{Si}\,\text{ii})\) | 13.97 \pm 0.08 | 9 |
| \(\log N(\text{Si}\,\text{iii})\) | 14.61 \pm 0.14 | 9 |
| \(\log N(\text{Fe}\,\text{ii})\) | 14.54 \pm 0.10 | 9 |
| The Warm Photoionized ISM | | |
| \(v (\text{km s}^{-1})\) | -77 | 5 |
| \(\log N(\text{Si}\,\text{ii})\) | 14.70 \pm 0.15 | 9 |
| \(\log N(\text{O}\,\text{iv})\) | 14.26 \pm 0.08 | 9 |

a Given the observed column density, we expect the line to be saturated. The reported value should therefore be treated as a lower limit.

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5 We note the low oxygen abundance \([O/H]\) determined by Heckman et al. (2001) based on O\(^{\text{ii}}\) absorption lines observed in FUSE spectra. Given the observed column density, however, we expect the line to be saturated. Therefore, the reported value should be treated as a lower limit.
comparison between known properties of the ISM near the progenitors of high-redshift GRBs and the ISM properties around NGC 1705-1. Here we discuss the insights we gain from the UV echelle spectra of nearby super star clusters for interpreting the afterglow absorption-line studies of distant GRB hosts.

4.1. Gaseous Structures of the ISM near NGC 1705-1

The complex velocity structure displayed in the absorption-line profiles of different ionization species indicates a multiphase ISM near the super star cluster NGC 1705-1. Based on FUSE observations of the starburst, Heckman et al. (2001) presented a comprehensive study of the thermal state of the ISM. These authors identified (1) a neutral medium, as demonstrated by H\textsc{i}, O\textsc{i}, Si\textsc{ii}, and Fe\textsc{ii} absorption; (2) a warm photoionized phase, as demonstrated by the H\textsc{α} emission nebula (Meurer et al. 1992; Marlowe et al. 1999) and N\textsc{ii} and S\textsc{iii} absorption; and (3) coronal gas, as demonstrated by the O\textsc{iv} absorption doublet. These results are well supported by our analysis of the STIS echelle observations.

Given the small velocity offset of the neutral gas ($v \approx 43 \text{ km s}^{-1}$) with respect to the nebular lines, Heckman et al. propose that the neutral gaseous clouds represent neutral ISM that has been engulfed by the expanding superbubble. Under this scenario, the distance of the neutral gas must be $d_{\text{neutral}} \approx 500$ pc, the observed size of the superbubble, and the gas density is required to be $n_{\text{neutral}} \approx 8 \text{ cm}^{-3}$ for effective self-shielding from the ionizing radiation of the star cluster. Together these constrain the cloud to be $\sim 10$ pc for producing the observed H\textsc{i} column density.

Given the large observed column density of O\textsc{iv} at $v \approx 77 \text{ km s}^{-1}$, Heckman et al. also concluded that the coronal gas cannot originate from behind the shocks induced by the expanding superbubble, but rather from blowout gas (superwinds) that is undergoing radiative cooling between photoionized fragments of the shells. In this picture, the ISM around NGC 1705-1 has been heated by both the expansion of superbubbles and the UV radiation of the central star cluster. The STIS echelle observations

Fig. 2.—Complex absorption profiles of heavy ions identified at the velocity of NGC 1705 in the HST STIS echelle spectrum. The three left columns show low-ionization species, and the right column shows high-ionization species. The zero relative velocity ($v = 0$) corresponds to $z = 0.00209$. Contaminating features are dotted out. Stellar photospheric features are present in transitions such as C\textsc{iv} and Si\textsc{iv}, shown as a broad, shallow component extending from $v = -500$ through 300 km s$^{-1}$. While strong low-ionization transitions such as C\textsc{ii} λ1334 and Si\textsc{ii} λ1260 are saturated, weaker transitions such as N\textsc{i}, S\textsc{ii} λ1259, and Fe\textsc{ii} λ1608 clearly exhibit two narrow components in the neutral ISM at $v = -15$ and $-45$ km s$^{-1}$. High-ionization transitions such as Al\textsc{iii}, C\textsc{iv}, and Si\textsc{iv} exhibit a dominant component that is systematically shifted to $v = -70$ km s$^{-1}$, coincident with the kinematic signatures of the O\textsc{iv} absorption doublet discussed in Heckman et al. (2001). We also note a weak contribution from highly ionized gas at $v > 0$ km s$^{-1}$, presumably from photospheric absorption. [See the electronic edition of the Journal for a color version of this figure.]
| \( J^a \) | \( E_J \) (cm\(^{-1}\)) | \( \lambda \) (\AA) | \( \log f \) | \( v_{\text{exp}} \) (km s\(^{-1}\)) | \( W^c \) (m\(\AA\)) | \( \log N \) | \( \log N_{\text{adopt}} \) |
|---------|-----------------|-------------|-----------|-----------------|-----------------|-----------|-----------------|
| C \( ii \) | 0.00 | 1277.2450 | -0.8816 | [-100, 40] | \(<18.4\) | \(<13.17\) | \(<13.17\) |
| C \( ii \) | 0.00 | 1560.3902 | -0.8808 | [-100, 40] | \(<39.6\) | \(<13.51\) | \(<\ldots\) |
| C \( ii \) | 0.00 | 1656.9283 | -0.8273 | [-100, 40] | \(<58.7\) | \(<13.44\) | \(<\ldots\) |
| C \( iv \) | 1/2 | 0.00 | 1334.5323 | -0.8935 | [-100, 40] | 625.4 ± 4.4 | \(>15.13\) | \(>15.13\) |
| C \( iv \) | 3/2 | 63.40 | 1335.7077 | -0.9397 | [-100, 40] | 276.8 ± 7.6 | \(14.39 ± 0.02\) | \(14.39 ± 0.02\) |
| O \( i \) | 2 | 0.00 | 1302.1685 | -1.3110 | [-60, 40] | 366.0 ± 4.8 | \(>15.24\) | \(>15.24\) |
| O \( i \) | 1 | 158.26 | 1304.8576 | -1.3118 | [-100, 40] | 55.2 ± 8.8 | \(14.05 ± 0.06\) | \(14.05 ± 0.06\) |
| Mg \( ii \) | 0.00 | 2852.9642 | 0.2577 | [-100, 40] | 349.3 ± 64.3 | \(12.54 ± 0.09\) | \(12.54 ± 0.09\) |
| Mg \( ii \) | 0.00 | 2796.3520 | -0.2130 | [-100, 40] | 1269.5 ± 34.3 | \(>13.97\) | \(>14.14\) |
| Mg \( ii \) | 0.00 | 2803.5310 | -0.5151 | [-100, 40] | 1146.5 ± 49.3 | \(>14.14\) | \(<\ldots\) |
| Al \( ii \) | 0.00 | 1670.7874 | 0.2742 | [-100, 40] | 585.8 ± 23.0 | \(>13.49\) | \(>13.49\) |
| Al \( iii \) | 0.00 | 1854.7164 | -0.2684 | [-100, 40] | 274.4 ± 52.1 | \(>13.39 ± 0.10\) | \(>13.43 ± 0.08\) |
| Si \( ii \) | 1/2 | 0.00 | 1260.4221 | 0.0030 | [-100, 40] | 583.6 ± 5.6 | \(>14.21\) | \(>14.83\) |
| Si \( ii \) | 1/2 | 0.00 | 1304.3702 | -1.0269 | [-100, 40] | 401.8 ± 6.6 | \(>14.81\) | \(<\ldots\) |
| Si \( ii \) | 1/2 | 0.00 | 1526.7066 | -0.8962 | [-100, 40] | 574.5 ± 11.0 | \(>14.83\) | \(<\ldots\) |
| Si \( ii \) | 3/2 | 287.24 | 1264.7377 | -0.0441 | [-100, 40] | 19.9 | \(<12.39\) | \(<12.39\) |
| S \( iii \) | 0.00 | 1259.519 | -1.7894 | \(<\ldots\) | \(<\ldots\) | \(<14.67 ± 0.10\) | \(14.65 ± 0.09\) |
| Cr \( ii \) | 0.00 | 2056.2539 | -0.9788 | [-100, 40] | \(<65.0\) | \(<13.42\) | \(<13.42\) |
| Fe \( ii \) | 9/2 | 0.00 | 1608.4511 | -1.2366 | [-100, 40] | 307.6 ± 19.0 | \(14.64 ± 0.06\) | \(14.64 ± 0.06\) |
| Fe \( ii \) | 9/2 | 0.00 | 1611.2005 | -2.8665 | [-100, 40] | \(<55.8\) | \(<15.60\) | \(<\ldots\) |
| Fe \( ii \) | 9/2 | 0.00 | 2260.7805 | -2.6126 | [-100, 40] | \(<55.5\) | \(<14.91\) | \(<\ldots\) |
| Fe \( ii \) | 9/2 | 0.00 | 2344.2140 | -0.9431 | [-100, 40] | 575.9 ± 24.8 | \(>14.33\) | \(<\ldots\) |
| Fe \( ii \) | 9/2 | 0.00 | 2374.4612 | -1.5045 | [-100, 40] | 379.8 ± 39.5 | \(>14.65\) | \(<\ldots\) |
| Fe \( ii \) | 9/2 | 0.00 | 2382.7650 | -0.4949 | [-100, 40] | 737.3 ± 37.7 | \(>14.08\) | \(<\ldots\) |
| Ni \( ii \) | 0.00 | 1370.1310 | -1.2306 | [-100, 40] | \(<21.6\) | \(<13.53\) | \(<13.53\) |
| Zn \( ii \) | 0.00 | 2026.1360 | -0.3107 | [-100, 40] | \(<85.7\) | \(<12.90\) | \(<12.90\) |

\(a\) Total angular momentum of the electron spin and orbital angular moment; \(E_J\) is the energy above the ground state.

\(b\) Velocity interval over which the equivalent width and column density are measured.

\(c\) Rest equivalent width.

\(d\) The S \( ii \) 11259 transition is contaminated by the Si \( ii \) 11260 transition from a foreground high-velocity cloud along the sight line. We determine \(N(S ii)\) using the VPFIT software package, including multiple components. Here we present the sum of the two narrow components at \(\Delta v = -45\) and \(-15\) km s\(^{-1}\) (see Fig. 1).
The black histogram represents the echelle spectrum, and the thin curve at the bottom represents the corresponding 1 σ array. A Voigt profile analysis that includes two H i components at $z = 0.00209$ (the position of the vertical dashed line) and $z = 0$ (the emission feature) yield log $N$($H$ i) = 20.05 ± 0.15 for NGC 1705 and log $N$($H$ i) = 19.7 for the Milky Way. The best-fit model is represented by the red curve with the yellow band marking the 1 σ uncertainties in the NGC 705 Lyα profile. The error is dominated by systematic uncertainty due to continuum placement, which is described by the nearly horizontal dashed line. Although the absorption feature is blended with the H i Lyα absorption from the Milky Way, the total neutral hydrogen absorption column density $N$($H$ i) is well constrained by the red damping wing. Our $N$($H$ i) measurements agree very well with previous measurements by Sahu (1998) and Heckman et al. (2001) based on HST GHRs and FUSE observations, respectively. We note that the absorption features at $\lambda < 1210$ Å are due to Si in $\lambda 1206$ transitions at $z \leq 0.00209$.

allow us to constrain the gas temperature at $T_{\text{coronal}} \sim 10^5$ K and a bulk motion of $b_0 \approx 12.6$ km s$^{-1}$.

### 4.2. Comparisons with the ISM Properties of High-Redshift GRB Hosts

The primary objectives of the present study are (1) to explore an alternative scenario in which young super star clusters provide a likely birth site for long-duration GRBs and (2) to examine whether available UV echelle spectra of nearby super star clusters offer additional insights for interpreting afterglow absorption-line studies of high-redshift bursts. Our current understanding of the host ISM around high-redshift bursts can be summarized as follows.

First, Prochaska et al. (2006) argued that the large neutral gas column observed along an afterglow sight line is located at $r = 100$–1000 pc from the GRB progenitor star, in order for Mg$^0$ to survive the intense UV radiation field. The associated heavy ions, such as C$^+$, Si$^+$, and Fe$^+$ in the neutral gas clouds, would subsequently be excited by the afterglow UV photons for producing the observed absorption features from their excited states (confirmed by Vreeswijk et al. 2007 for GRB 060418). The neutral gas clouds in the ISM model of NGC 1705-1 from Heckman et al. (2001) offer a natural candidate for the presence of dense neutral clouds in the vicinity of a GRB progenitor at high redshift. Note that the observed $N$($H$ i) along the sight line toward NGC 1705-1 is more similar to the strong Lyman limit systems of $N$($H$ i) = 19–20 observed in the hosts of GRBs 021004, 050908, and 060526 (Jakobsson et al. 2006). Higher column density absorbers would imply either a smaller cloud size or higher neutral gas density. Nonetheless, should a GRB occur in NGC 1705-1, the neutral gas at $r \sim 500$ pc would still remain neutral under the afterglow radiation field, but would be excited to produce the commonly observed transitions from excited ions.

In addition, the ISM of NGC 1705 exhibits little or no trace of molecular gas, neither CO nor H$_2$, despite the recent starburst episode $\sim$10 Myr ago and ongoing star formation $\sim$0.06 $M_\odot$ yr$^{-1}$. NGC 1705 resembles the Small Magellanic Cloud (SMC) both in size and in the total metal content, but has on average a substantially smaller molecular fraction: $f_{H_2} < 5.2 \times 10^{-4}$ for NGC 1705 (Table 1) versus $f_{H_2} \lesssim 0.01$ near star-forming regions in the SMC (Tumlinson et al. 2002). The super star cluster NGC 1705 near the center of NGC 1705 is among the brightest star clusters in the local universe (Meurer et al. 1995), containing massive stars of $>30 M_\odot$ and $\sim 10$ Myr old.

The lack of molecules in the ISM around NGC 1705-1 is reminiscent of what is observed in the high column density clouds surrounding GRB progenitors (Hatsukade et al. 2007; Tumlinson et al. 2007). The low molecular fraction and dust extinction for moderately enriched ISM and high gas density appear to be remarkably similar, implying that the lack of molecules and dust may be due to the enhanced UV radiation from massive stars in the star-forming region that hosts the GRB progenitor (e.g., Hoopes et al. 2004; Tumlinson et al. 2007).

We further note that similar to what is observed in the afterglow spectra of high-redshift GRBs, low-ionization species in NGC 1705-1 are more confined in a narrow velocity interval, whereas high-ionization transitions exhibit a larger velocity spread. The apparent offset in the velocity profiles of low-ionization (such as Fe ii) and high-ionization transitions (such as C iv and Si iv) observed toward NGC 1705-1 (Fig. 2) is now understood as due to starburst-driven outflows, based on extensive imaging and spectroscopy studies. It suggests that important clues for possible starburst nature in GRB host galaxies may already be learned based on afterglow spectra alone. This is particularly valuable because the host galaxies of distant GRBs are faint and challenging to find in emission. Of the six GRB hosts studied in Chen et al. (2007), we identify velocity offsets between Si ii and C iv/Si iv over the range from $v = -65$ to $-200$ km s$^{-1}$ along the sight lines toward GRBs 021004, 050730, 050908, and 060418.

Finally, we present in Table 3 a direct comparison of different ISM properties between NGC 1705-1 and GRB hosts. The table shows that the two sources occupy a comparable parameter space. In particular, absorption-line studies of GRB host galaxies show that the host ISM of high-redshift GRBs exhibits clear $\alpha$-element

| Property | NGC 1705-1 | GRB Hosts |
|----------|------------|-----------|
| log $N$($H$ i) | [20.1, 21.2] | [19, 8, 22.5] |
| $[Z/H]$ | $-0.6 \pm 0.1$ | $[-2.2, -0.2]$ |
| $[\alpha/Fe]$ | $+0.5 \pm 0.2$ | $[+0.4, +0.9]$ |
| $[Ne/Fe]$ | $-1.5 \pm 0.2$ | $[-2.0, -0.5]$ |
| $f_{H_2}$ | $< 5.2 \times 10^{-7}$ | $< 3 \times 10^{-7}$ |
| $A$ | $\sim 0.0$ | $[0.0, 0.2]$ |
| $n_{\text{neutral}}$ (pc$^{-3}$) | $\lesssim 500$ | $100–1000$ |

$^a$ Measurements for the ISM of GRB hosts are from Prochaska et al. (2007).

$^b$ Measurements for GRB hosts are from Tumlinson et al. (2007).
enhancement, with little dust extinction/depletion along the sight lines toward the afterglows.

The similarity in the ISM properties shows that this scenario for long-duration GRBs originating in massive star clusters is at least viable. The relatively low nitrogen abundance also signifies the young age of the progenitor star clusters, because nitrogen is produced primarily in intermediate-mass asymptotic giant branch (AGB) stars (e.g., Prochaska et al. 2007). NGC 1705-1 is unique among known super star clusters locally, because of its young age and massive stellar content. Conclusive evidence requires a large UV spectroscopic sample of nearby super star clusters.

These data are necessary for a complete statistical analysis of their ISM properties to be compared with afterglow absorption-line studies. For example, a comparison of the $N$(H i) distribution and the size distribution of neutral clouds in the vicinity of young star clusters may offer important support, or otherwise, for the star cluster origin of long-duration GRBs. We expect that a direct comparison with known statistical properties of high-redshift GRB hosts will allow us to identify the key physical parameters that facilitate the formation of GRBs. The direct evidence of inflow gas around NGC 1705, as evidenced by the redshifted components seen in C iv and Si iv, is also worth noting. A larger sample may be useful for studying gas accretion around galaxies. Future spectroscopic observations of nearby super star clusters using the Cosmic Origin Spectrograph to be installed on the HST are necessary.

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REFERENCES

Ashplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes, III, & F. N. Bash (San Francisco: ASP), 25

Calzetti, D., Kinney, A., & Storchi-Bergmann, T. 1994, ApJ, 429, 582

Chen, H.-W., Prochaska, J. X., Ramírez-Ruiz, E., Bloom, J. S., Dessauges-Zavadsky, M., & Foley, R. J. 2007, ApJ, 663, 420

Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913

Crowther, P. 2007, ARA&A, 45, in press (astro-ph/0610356)

Della Valle, M., et al. 2006, Nature, 444, 1050

Efremov, Y. 2001, in Gamma-Ray Bursts in the Afterglow Era, ed. E. Costa, F. Della Valle, M., et al. 2006, Nature, 444, 1050

———. 2006b, A&A, 451, L47

Gal-Yam, A., et al. 2006, Nature, 444, 1053

Greve, A., Becker, R., Johansson, L., & McKeith, C. 1996, A&A, 312, 391

Hansen, B., & Murali, C. 1998, ApJ, 505, L15

Hatsukade, B., et al. 2007, PASJ, 59, 67

Heckman, T. M., Sembach, K. R., Meurer, G. R., Strickland, D. K., Martin, C. L., Calzetti, D., & Leitherer, C. 2001, ApJ, 554, 1021

Henry, R. B. C., Edmunds, M. G., & Köppen, J. 2000, ApJ, 541, 660

Hjorth, J., et al. 2003, Nature, 423, 847

Hoopes, C., et al. 2004, ApJ, 612, 825

Jakobsson, P., et al. 2006, A&A, 460, L13

Lamb, S. A., Hjellming, M. S., Gallagher, J. S., III, & Hunter, D. A. 1985, ApJ, 291, 63

Lee, H., & Skillman, E. 2004, ApJ, 614, 698

Loeb, A., & Perna, R. 1998, ApJ, 503, L35

Malesani, D., et al. 2004, ApJ, 609, L5

Marlowe, A., Meier, G., & Heckman, T. 1999, ApJ, 522, 183

Meurer, G. R., Freeman, K. C., Dopita, M. A., & Cacciari, C. 1992, AJ, 103, 60

Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, AJ, 110, 2665

Meurer, G. R., Staveley-Smith, L., & Killeen, N. E. B. 1998, MNRAS, 300, 705

Motijaz, M., Kewley, L., Kirshner, R. P., Stanek, K. Z., Challis, P., Garnavich, P. M., Greene, J. E., & Prieto, J. L. 2007, AJ, submitted (astro-ph/0701246)

Patat, F., et al. 2001, ApJ, 555, 900

Podsiadlowski, P., Mazzali, P. A., Nomoto, K., Lazzati, D., & Cappellaro, E. 2004, ApJ, 607, L17

Prochaska, J. X., Chen, H.-W., & Bloom, J. S. 2006, ApJ, 648, 95

Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. 2007, ApJ, 666, 267

Prochaska, J. X., et al. 2004, ApJ, 611, 200

Sahu, M. 1998, AJ, 116, 1205

Sahu, M., & Blades, J. 1997, ApJ, 484, L125

Savage, B., & Sembach, K. 1991, ApJ, 379, 245

Savaglio, S. 2006, New J. Phys., 8, 195

Smith, L., & Gallagher, J., III. 2001, MNRAS, 326, 1027

Soderberg, A. M., Nakar, E., Berger, E., & Kulkarni, S. 2006, ApJ, 638, 930

Sonnenstrucker, P., Friedman, S., Welty, D., York, D., & Snow, T. 2002, ApJ, 576, 241

Stanek, K., et al. 2003, ApJ, 591, L17

Starling, R. L. C., Wijers, R. A. M. J., Wiersema, K., Rol, E., Curran, P. A., Kouveliotou, C., van der Horst, A. J., & Heemskerk, M. H. M. 2007, ApJ, 661, 787

Tosi, M., Sabha, E., Bellazzini, M., Aloisi, A., Greggio, L., Leitherer, C., & Montegriffo, P. 2001, AJ, 122, 1271

Tumlinson, J., et al. 2002, ApJ, 566, 857

Tumlinson, J., Prochaska, J., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. 2007, ApJ, submitted (astro-ph/0703666)

van Putten, M. H. P. M. 2004, ApJ, 611, L81

Vázquez, G., et al. 2004, ApJ, 600, 162

Vreeswijk, P. M., et al. 2007, A&A, 468, 83

Wolfé, A. M., Prochaska, J. X., & Gwaiser, E. 2003, ApJ, 593, 215

Woosley, S., & Bloom, J. 2006, ARA&A, 44, 507

Woosley, S., & Heger, A. 2006, ApJ, 637, 914

York, D., Gault, A., Rybski, P., Gallagher, J., Blades, J., Morton, D., & Wamsteker, W. 1990, ApJ, 351, 412