Probing the circumstellar medium of GRB afterglows through absorption-line observations

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A systematic search of Wolf–Rayet wind signatures, as represented by blue-shifted, high-velocity ($|\Delta v| = 1000–5000$ km s$^{-1}$) C IV $\lambda\lambda$ 1548, 1550 absorption doublet has yielded an estimate of 20% for the incidence of these C IV absorbers near the host galaxies of gamma-ray bursts (GRBs). This is consistent with what is observed near classical damped Lyα absorbers that have a comparable neutral hydrogen column density as the GRB host galaxies. A detailed ionization analysis of these absorbers, including the associated low-ionization species, shows that the majority in fact originate in foreground galaxies along the sightline, rather than in the vicinity of the GRB afterglows. Taking into account the enhanced afterglow radiation field, the lack of Wolf–Rayet signatures can be applied to constrain the C/He ratio and the density contrast of the winds in the vicinity of GRB progenitor stars.

Keywords: gamma-ray burst; ISM abundances; Wolf–Rayet winds

1. Background

The origin of long-duration gamma-ray bursts (GRBs) is now well-established (Woosley & Bloom 2006). With Wolf–Rayet stars as likely progenitors for long-duration GRBs (MacFadyen & Woosley 1999), it is expected that the circumburst medium has been regulated by the ejected winds (with a terminal wind speed of $\leq 5000$ km s$^{-1}$ or less; van der Hucht 2001) throughout the lifetime of the progenitor star. The presence of a Wolf–Rayet wind in the circumburst medium can, in principle, be demonstrated in an early time, single-epoch afterglow spectrum that shows a narrow, blue-shifted, high-velocity C IV $\lambda\lambda$ 1548, 1550 absorption doublet (van Marle et al. 2005). Indeed, these have been reported towards GRB 021004 at $z_{\text{GRB}} = 2.329$ (Møller et al. 2002; Mirabal et al. 2003; Schaefer et al. 2003; Fiore et al. 2005; Fynbo et al. 2005; Starling et al. 2005; see also Lazzati et al. 2006), GRB 030226 (Klose et al. 2004) and GRB 050505 at $z_{\text{GRB}} = 4.2741$ (Berger et al. 2006), but the origin of these C IV absorption components is uncertain for three reasons.

First, the likelihood of finding an intervening absorber over $\Delta v = 1000$–5000 km s$^{-1}$, which is uncorrelated with the GRB host but associated with a foreground galaxy along the sightline, is non-negligible. Second, the presence of an
intense ultraviolet radiation field from the optical afterglow substantially increases the ionization of the circumburst medium, prohibiting most ions from surviving at close distances to the afterglow. Finally, the observed C IV abundance alone is insufficient for constraining the ionization state of the gas around the afterglow. A complete consideration of all species at different ionization stages is necessary.

2. A sample of GRB afterglow spectra

We have compiled a sample of five GRB afterglow spectra for which no prior knowledge of the line-of-sight absorption-line properties was available (Chen et al. submitted). The qualities of these spectra are such that the C IV λ1548, 1550 absorption doublet can be resolved (i.e. a spectral resolution δν < 180 km s\(^{-1}\)) and have a signal-to-noise ratio of \(S/N > 7\) per resolution component in order to detect the weaker C IV λ1550 transition at a greater than 3σ confidence level to an EW limit of 0.1 Å. This afterglow sample is supplemented with three additional sightlines from the literature for which the line-of-sight properties have been studied in detail. We search for blue-shifted, high-velocity components of C IV within |Δν| ≤ \(v_\text{term}\) km s\(^{-1}\) in these afterglow spectra. The velocity threshold \(v_\text{term}\) is chosen to match the terminal velocity observed for galactic Wolf–Rayet stars with terminal wind velocity of \(\leq 5000\) km s\(^{-1}\) or less. The search for high-velocity C IV components is therefore carried out at |Δν| ≤ \(v_\text{term} = 5000\) km s\(^{-1}\). An additional selection threshold for |Δν| ≤ −1000 km s\(^{-1}\) is applied based on the maximum velocity of galactic winds observed in starburst galaxies at \(z > 1\) (e.g. Adelberger et al. 2005). The nature of C IV within Δν > −1000 km s\(^{-1}\) becomes more ambiguous due to possibility of a large-scale galactic wind or even gas with large infall velocities. We therefore exclude this region from consideration. Figure 1 shows the C IV doublet of four afterglow sightlines in our sample.

3. Implications from the lack of Wolf–Rayet signatures

Our search for a blue-shifted, high-velocity C IV absorption doublet has shown that the majority of GRB lines of sight do not exhibit the expected Wolf–Rayet signatures. Taking into account existing afterglow light-curve observations, we can examine whether the lack of Wolf–Rayet signatures arises as a result of the circumburst medium being ionized by the intense ultraviolet radiation field of the afterglow.

To assess the impact of the afterglow over the circumburst medium, we estimate the number of ionizing photons released to the surrounding medium prior to the onset of the spectroscopic observations \(t_\text{obs}^{\text{spec}}\). We use the afterglow of GRB 050820 as an example. We first note that the C\(^{4+}\) ions have a recombination rate coefficient \(\alpha_R(C^{4+}) \sim 10^{-11.5}\) cm\(^3\) s\(^{-1}\) (Nahar & Pradhan 1997), implying a characteristic recombination time-scale of \(t_\text{rec}(C^{4+}) \sim 1\) year \(\gg t_\text{obs}^{\text{spec}}\) for a gas temperature of \(T \sim 10^{4.5}\) K and electron density \(n_e \sim 10^4\) cm\(^{-3}\). Therefore, the ionization fraction of the circumburst medium can be approximated by considering only the amount of ionizing photons available to ionize C\(^{3+}\).

In addition, we note that the ionization potential of He\(^+\) traces closely to that of C\(^{3+}\). The He\(^+\) ions, therefore, naturally shield ionizing photons for the C\(^{3+}\) ions, and must be accounted for in photoionization calculations. Following
Chen et al. (submitted), we estimate the minimum radius below which greater than 95% of the \( C^3+ \) ions are ionized according to

\[
    r_{\text{min}} = \left[ \frac{\phi_\gamma \sigma_{ph}(C^3+)}{1.2 \times 10^{38} \times (3 + \ln A)} \right]^{1/2} \text{ pc},
\]

where \( \phi_\gamma \) is the total number of ionizing photons, \( \sigma_{ph} \) is the ionization cross-section and \( A \approx 1 + 2/3(C/\text{He})^{-1} \) accounts for the presence of He\(^+\) for shielding.

Adopting the \( R \)-band light curve of GRB 050820 (Vestrand et al. 2006), we estimate an isotropic release of \( \phi_\gamma(h\nu = 13.6–27.2 \text{ eV}) \approx 7.2 \times 10^{60} \) photons and \( \phi_\gamma(h\nu = 8–13.6 \text{ eV}) \approx 10^{61} \) photons before the observations of the afterglow spectra took place \( \Delta t = t_{\text{obs}} = 3240 \) s. We calculate \( A = 168 \) for a solar abundance pattern and derive \( r_{\text{min}} = 36 \) pc for GRB 050820. The lack of Wolf–Rayet wind signatures in the host of GRB 050820, therefore, indicates that if such winds exist and give rise to strong \( C^4 \) absorption, then it did not reach beyond 30 pc.

4. The nature of blue-shifted, high-velocity \( C^4 \) absorbers

In addition to the blue-shifted, high-velocity \( C^4 \) absorbers reported towards GRB 021004, these features have been identified towards GRB 030223 at \( z_{\text{GRB}} = 1.986 \) (Klose et al. 2004; Shin et al. submitted) and towards GRB 050730 at \( \Delta v = 1500 \text{ km s}^{-1} \) (Chen et al. submitted). While a Wolf–Rayet wind from the GRB progenitor is a natural candidate for explaining these absorbers, there exist various uncertainties.
First, we estimate the probability of finding a random absorber along the line-of-sight at $z_{\text{C,IV}} < z_{\text{GRB}}$. Random surveys towards quasar lines of sight have shown a mean number density per unit redshift interval of $n_{\text{C,IV}}(z=2) = 1.8 \pm 0.4$ for C IV absorbers of rest-frame absorption equivalent width $\text{EW}(\lambda 1548) > 0.4$ Å and $n_{\text{C,IV}}(z=2) \sim 5$, including weaker ones $\text{EW}(\lambda 1548) > 0.15$ Å (Steidel 1992). An accurate estimate of the incidence of C IV absorbers over $D_v \sim 1000$–$5000$ km s$^{-1}$ from the GRB hosts requires a statistically unbiased sample of afterglow sightlines. Our small sample of five GRB spectra were collected and analysed with no prior knowledge of the line-of-sight properties. We show in Chen et al. (submitted) that only a C IV absorber at $D_v \approx 1500$ km s$^{-1}$ towards GRB 050730 is found. The total redshift pathlength in their sample of five was $\Delta z = 0.23$. Therefore, the probability of detecting one random C IV absorber of $\text{EW}(\lambda 1548) > 0.4$ is 27% and the probability of detecting two such strong absorbers is 6%. At a lower threshold $\text{EW}(\lambda 1548) > 0.15$, the probability of detecting one(two) random absorber at lower redshifts is 36%(21%). This exercise shows that the likelihood of finding a contaminating absorber at a cosmological distance to the host galaxy is non-negligible. Deep images of the field around GRB 050730 are not available, but images around GRB 021004 (Fynbo et al. 2005; see also Chen et al. submitted) show a faint companion at 0.3" from the host galaxy of the GRB, supporting the scenario that at least one of the C IV components originates in a foreground galaxy.

Next, we analyse the ionization state of the C IV absorbers based on the observed abundance ratios of C$^+$ to C$^{3+}$ and Si$^+$ to Si$^{3+}$. Figure 2 shows the two absorption components at $|\Delta v| = 2700$ (component 1) and 2900 km s$^{-1}$ (component 2), respectively. A strong Ly$\alpha$ absorption feature is present at the location of the two blue-shifted, high-velocity C IV components, but not resolved in this low-resolution spectrum. In addition to the strong H$\ I$ Ly$\alpha$ transition, we also observe abundant low ions, such as C$^+$, as evident by the C$\ II$ $\lambda 1334$ transition at the location of component 1. The large contrast in the observed relative column densities of C$^+$ and C$^{3+}$ for components 1 and 2 suggests that they do not share the same origin.

We use the Cloudy software (Ferland et al. 1998; v. 06.02) to calculate the expected population ratios between different ionization stages of carbon and silicon for clouds of plane parallel geometry and under photoionization equilibrium$^1$. We have assumed a metallicity of 0.1 solar and log $N$(HI$)=15$, appropriate for intervening, strong C IV absorbers along quasar lines of sight (e.g. Cowie et al. 1995). The results are not sensitive to the adopted metallicity and $N$(HI). We also note that the assumed solar relative abundances are not relevant because we compare pairs of ions for the same elements. Figure 3 shows the abundance ratios of C$^+$ to C$^{3+}$ and Si$^+$ to Si$^{3+}$ versus the ionization parameter $U \equiv \phi_\gamma / c n_H$, which represents the number of ionizing photons available per hydrogen particle.

$^1$Fiore et al. (2005) presented a photoionization analysis of these absorbers using the Cloudy software as well. Our analysis differs from Fiore et al. in two important aspects. First, the C$\ II$ transition of component 1 and C IV transitions of component 2 are observed to be saturated and should therefore be treated as lower limits to the underlying absorption column density. Second, our analysis compares only carbon to carbon and silicon to silicon. Therefore, it does not presume an abundance pattern. The echelle spectrum demonstrates that the C$^+$ and the C$^{3+}$ ions share the same kinematic features (figure 2). The observed $N$(C$\ II$)$/N$(C IV) therefore places a robust upper limit to the ionization fraction.
Comparison between observations and expectations of photoionized gas in the intergalactic medium shows that the observed relative ionic abundances for the two C IV components can be naturally explained under photoionization equilibrium with the meta-galactic radiation field. In particular, the upper limit on the ionization parameter for component 1 indicates that a low ionizing intensity is favoured, inconsistent with the intense radiation field expected in the presence of the GRB afterglow. We further note that the presence of a bright afterglow would substantially increase the ionization parameter to $\log \frac{\phi_i}{cn_i} \gg 0$, but owing to the transient nature of the afterglow the condition of photoionization equilibrium is not applicable.

In summary, our analysis shows that (i) at least one of the two prominent features found along the sightline towards GRB 021004 is of intergalactic origin and (ii) the majority of GRB afterglow spectra do not show the expected Wolf–Rayet signatures traced by the C IV $\lambda\lambda1548, 1550$ transitions. The lack of Wolf–Rayet signatures in the circumburst environment can be understood as due to the intense UV radiation field of the afterglows. Our estimates show that ionizing photons from the afterglow can ionize C$^{3+}$ to beyond 30 pc radius from the progenitor stars.

Figure 2. Absorption profiles of H I Ly$\alpha$ $\lambda1215$, C IV $\lambda\lambda1548, 1550$, Si IV $\lambda\lambda1393, 1402$, C II $\lambda1334$, Si II $\lambda1526$ and Al II $\lambda1670$ observed in the host of GRB 021004. The same as figure 2, where contaminating absorption features are dotted out. The dashed-dotted lines indicate the normalized continuum and zero level for guide. The 1-$\sigma$ error array is shown in thin, cyan line. Zero relative velocity corresponds to $z = 2.32897$. Over the velocity interval from $\Delta v = -5000$ to $-1000$ km s$^{-1}$, we identify two absorption components at $\Delta v = -2675$ and $-2900$ km s$^{-1}$, respectively.
To allow the C$^{3+}$ ions to survive in the vicinity of the afterglow, Starling et al. (2005) proposed a structured jet model, under which the ionization of the circumstellar medium is dominated by a narrow and fast-moving jet while the line of sight encompasses a wider and slower-moving jet through the wind, where the C$^{3+}$ ions can survive at smaller distances to the burst. In this scenario, the absorption-line profiles are expected to show evidence of partial coverage of the light, which is not observed in the data. We note that the presence of abundant He$^{+}$ ions and a large density contrast in the wind can provide necessary shielding for the C$^{3+}$ ions. The absence of high-velocity C IV components in the vicinity of GRB afterglows may provide useful constraints on the clumpiness of the winds in the vicinity of GRB progenitor stars.

This work was supported in part by NASA grant NNG06GC36G and NSF grant AST-0607510.

References


