A Global Photoionization Response to Prompt Emission and Outliers: Different Origin of Long Gamma-ray Bursts?

J. Wang\textsuperscript{1,2}, L. P. Xin\textsuperscript{1}, Y. L. Qiu\textsuperscript{1}, D. W. Xu\textsuperscript{1,2}, and J. Y. Wei\textsuperscript{1,2}

\textsuperscript{1}Key Laboratory of Space Astronomy and Technology, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, People’s Republic of China; wj@bao.ac.cn
\textsuperscript{2}School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing, People’s Republic of China

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Abstract

By using the line ratio C\textsubscript{IV} λ1549/C\textsubscript{II}λ1335 as a tracer of the ionization ratio of the interstellar medium (ISM) illuminated by a long gamma-ray burst (LGRB), we identify a global photoionization response of the ionization ratio to the photon luminosity of the prompt emission assessed by either $L_{\text{iso}}/E_{\text{peak}}$ or $L_{\text{iso}}/E_{\text{peak}}^2$. The ionization ratio increases with both $L_{\text{iso}}/E_{\text{peak}}$ and $L_{\text{iso}}/E_{\text{peak}}^2$ for a majority of the LGRBs in our sample, although there are a few outliers. The identified dependence of C\textsubscript{IV}/C\textsubscript{II} on $L_{\text{iso}}/E_{\text{peak}}^2$ suggests that the scatter of the widely accepted Amati relation is related to the ionization ratio in the ISM. The outliers tend to have relatively high C\textsubscript{IV}/C\textsubscript{II} values as well as relatively high C\textsubscript{IV}/Si\textsubscript{IV} λ1403 ratios, which suggests an existence of Wolf–Rayet stars in the environment of these LGRBs. We finally argue that the outliers and the LGRBs following the identified C\textsubscript{IV}/C\textsubscript{II}–$L_{\text{iso}}/E_{\text{peak}}$ ($L_{\text{iso}}/E_{\text{peak}}^2$) correlation might come from different progenitors with different local environments.

Key words: galaxies: ISM – gamma-ray burst: general – methods: statistical

1. Introduction

Long gamma-ray bursts (LGRBs) are the most powerful explosions occurring in local universe (the nearest one is GRB 980425 at $z = 0.008$, Galama et al. 1998) to very high redshift (e.g., Salvaterra et al. 2009; Tanvir et al. 2009). Currently, the most distant one reported in the literature is GRB 090429B with a photometric redshift of $z = 9.4$ (Cucchiara et al. 2011). The detection of the associated supernova in a few LGRBs (see Cano et al. 2017 for a recent review) strongly supports that LGRBs originate from the core-collapse of young massive stars ($\geq 25 M_\odot$; e.g., Woosley & Bloom 2006; Hjorth & Bloom 2012 and references therein). The GRB’s afterglow at a wide wavelength range from radio to X-ray is produced through the synchrotron radiation when the jet ignites in the core-collapse impacts and shocks the surrounding medium (e.g., Meszaros & Rees 1997; Sari et al. 1998).

Within the first hours after the onset of a burst, the powerful afterglows of LGRBs illuminate not only the interstellar medium (ISM) of their host galaxies, but also the intergalactic medium, which produces an afterglow optical spectrum associated with multiple strong absorption lines of metals with different ionization stages at different redshifts (e.g., Fynbo et al. 2009; de Ugarte Postigo et al. 2012). The spectra provide us with an opportunity to study the properties of the medium at a GRB’s local environment and intervening absorption clouds located between the host galaxy and the observer (e.g., Butler et al. 2003; Savaglio et al. 2003; Prochaska et al. 2006, 2007; Kawata et al. 2006; Totani et al. 2006; Tejos et al. 2007, 2009; Vreeswijk et al. 2007; D’Elia et al. 2009, 2010; Vergani et al. 2009; Wang 2013).

A response of the host galaxy environment to both prompt and afterglow emission has been proposed and observed for a long time. The theoretical study in Perna et al. (2003) suggested that the silicates can be destroyed by the strong X-ray/UV radiation (see also Waxman & Draine 2000). The photoionization effect due to the prompt and afterglow emission of GRBs has been identified in the X-ray spectra of a few bursts (e.g., Amati et al. 2000; Antonelli et al. 2000; Piro et al. 2000). Due to the afterglow evolution, an evolution of photoionization of the medium around the progenitors has been put forward in Perna & Loeb (1998), which is subsequently supported by the observed time variability of absorption lines in a few bursts (e.g., GRB 010222, Mirabal et al. 2002; GRB 020813, Dessauges-Zavadsky et al. 2006; GRB 060418, Vreeswijk et al. 2007; GRB 060206, Hao et al. 2007; GRB 080310, Vreeswijk et al. 2013; De Cia et al. 2012; GRB 100901, Hartog et al. 2013). In addition, with a sample of 69 low-resolution afterglow spectra, de Ugarte Postigo et al. (2012) revealed a global weak dependence of the ionization ratio quantified by the line strength parameter on the rest-frame isotropic prompt energy $E_{\text{iso}}$ in 1–1000 keV band.

In this paper, we identify a global photoionization response of the ISM to GRB’s prompt emission by instead focusing on the role of high energy ionizing photon flux. The result further motivates us to suspect that there are two kinds of origins of LGRBs. The paper is organized as follows. The sample selection is presented Section 2. Section 3 shows the results and implications.

2. Sample

Our aim is to study the global photoionization response of the host galaxy ISM to LGRB’s prompt emission. We adopt the line ratio of C\textsubscript{IV} λ1548,1550 and C\textsubscript{II}/C\textsubscript{II} $\lambda\lambda1334,1335$ as a tracer of the ionization ratio of the ISM of individual LGRBs, both because the two lines are usually quite strong in the afterglow spectra and because the ionization potential of C\textsubscript{IV} is as high as 47.89 eV. We compile a sample of Swift (Gehrels et al. 2004) LGRBs with reported measurements of two absorption lines and prompt emission. Our sample is mainly compiled from de Ugarte Postigo et al. (2012), which published a sample of low-resolution afterglow spectra of 69 LGRBs. For
the bursts with measurements (including both detection and upper limit) of both C IV and C II, the common objects with a measurement of prompt emission is extracted from Ghirlanda et al. (2018) and Nava et al. (2012). The sample is finally composed of 20 LGRBs and is tabulated in Table 1, along with the references. Columns (1) and (2) list the identification and the measured redshift of each LGRB, respectively. The measured equivalent widths (EWS) of $\lambda 1335$, C IV$\lambda 1549$, and Si IV$\lambda 1403$ absorption lines are given in Columns (3), (4), and (5), respectively. The logarithmic line ratio of C IV/C II is listed in column (6). Columns (7) and (8) are the rest-frame isotropic prompt luminosity and peak energy based on the standard band spectrum. All the errors reported in the table correspond to the 1σ significance level after taking into account the proper error propagation.

### 3. Results and Discussion

#### 3.1. C IV/C II: A Global Photoionization Response of ISM to LGRBs’ Prompt Emission

A global ionization response of ISM to the prompt emission of LGRBs is shown in Figure 1 in which the line ratio of C IV/C II

| GRB  | $z_{GRB}$ | EW(C IV $\lambda 1549$) (Å) | EW(C II/$C$ II$^+$ $\lambda 1335$) (Å) | EW(Si IV $\lambda 1549$) (Å) | log(C IV/C II) | log $L_{iso}$ (ergs$^{-1}$) | log $E_{peak}$ (keV) | References
|------|-----------|--------------------------|---------------------------------|--------------------------|----------------|--------------------------|--------------------------|----------|
| 050401 | 2.89 | 3.08 ± 0.77 | 2.57 ± 0.26 | <1.50 | −0.08 ± 0.12 | 53.30 ± 0.02 | 2.69 ± 0.09 | 1, 5 |
| 050908 | 3.34 | 0.24 ± 0.04 | 3.25 ± 0.05 | 0.59 ± 0.04 | 1.36 ± 0.12 | 51.92 ± 0.07 | 2.29 ± 0.08 | 1, 4 |
| 050922C | 2.22 | 0.31 ± 0.06 | 1.27 ± 0.03 | 0.43 ± 0.33 | 0.61 ± 0.08 | 53.28 ± 0.01 | 2.62 ± 0.12 | 1, 4 |
| 060124 | 2.3 | <0.7 | 2.9 ± 0.22 | <0.5 | >0.62 | 53.15 ± 0.01 | 2.80 ± 0.11 | 1, 4 |
| 0601210 | 3.91 | 4.32 ± 0.08 | 8.63 ± 0.05 | 3.05 ± 0.06 | 0.30 ± 0.01 | 52.78 ± 0.06 | 2.76 ± 0.14 | 1, 4 |
| 060714 | 2.71 | 2.83 ± 0.13 | 3.53 ± 0.11 | 1.56 ± 0.11 | 0.10 ± 0.02 | 52.15 ± 0.03 | 2.37 ± 0.20 | 1, 4 |
| 070110 | 2.35 | 1.15 ± 0.09 | 0.93 ± 0.09 | 0.42 ± 0.09 | −0.08 ± 0.05 | 51.65 ± 0.07 | 2.57 ± 0.20 | 1, 4 |
| 070411 | 2.95 | 0.71 ± 0.13 | 2.56 ± 0.13 | 0.66 ± 0.11 | 0.56 ± 0.08 | 51.72 ± 0.04 | 2.68 ± 0.09 | 1, 4 |
| 071031 | 2.69 | 1.21 ± 0.04 | 2.18 ± 0.04 | 0.75 ± 0.04 | 0.26 ± 0.02 | 52.18 ± 0.04 | 1.64 ± 0.09 | 1, 4 |
| 080319C | 1.95 | <2.88 | 3.59 ± 0.24 | <1.87 | >0.10 | 52.98 ± 0.01 | 3.24 ± 0.13 | 1, 4 |
| 080603B | 2.69 | 1.05 ± 0.04 | 1.19 ± 0.04 | 0.43 ± 0.04 | 0.05 ± 0.02 | 53.08 ± 0.02 | 2.58 ± 0.09 | 1, 4 |
| 080605 | 1.64 | <6.89 | 5.11 ± 0.30 | … | >0.13 | 53.51 ± 0.02 | 2.82 ± 0.03 | 1, 4 |
| 080721 | 2.59 | 1.98 ± 0.19 | 4.46 ± 0.17 | 0.84 ± 0.04 | 0.35 ± 0.04 | 54.01 ± 0.06 | 3.24 ± 0.06 | 1, 4 |
| 080810 | 3.35 | <0.43 | 3.13 ± 0.21 | <0.21 | >0.86 | 52.97 ± 0.04 | 3.17 ± 0.10 | 1, 4 |
| 080808 | 1.97 | 1.41 ± 0.10 | 1.04 ± 0.07 | 0.44 ± 0.07 | −0.13 ± 0.04 | 51.48 ± 0.04 | 2.43 ± 0.09 | 1, 4 |
| 080928 | 1.69 | <1.44 | 2.12 ± 0.26 | <0.26 | >0.17 | 51.48 ± 0.04 | 2.30 ± 0.09 | 1, 4 |
| 090516 | 4.11 | 5.81 ± 0.04 | 5.87 ± 0.10 | 1.72 ± 0.04 | 0.00 ± 0.01 | 52.86 ± 0.02 | 2.97 ± 0.34 | 1, 4 |
| 090812 | 2.45 | 1.94 ± 0.21 | 1.12 ± 0.08 | 0.57 ± 0.12 | −0.24 ± 0.06 | 52.98 ± 0.04 | 3.51 ± 0.14 | 1, 4 |
| 110205 | 2.22 | 1.31 ± 0.25 | 0.73 ± 0.20 | … | −0.25 ± 0.14 | 52.40 ± 0.06 | 2.85 ± 0.15 | 2, 4 |
| 140624 | 2.28 | 1.80 ± 0.31 | 5.02 ± 0.21 | 2.01 ± 0.25 | 0.45 ± 0.08 | 53.30 ± 0.02 | 2.45 ± 0.09 | 3 |
is used as a tracer of the ionization ratio of the ISM within the line of sight of an observer. Instead of using $E_{\text{iso}}$ as an indicator of the strength of the prompt emission in the study of de Ugarte Postigo et al. (2012), the left panel in Figure 1 plots $\text{CIV}/\text{CII}$ as a function of $L_{\text{iso}}/E_{\text{peak}}$. Based on the definition of the band spectrum, $L_{\text{iso}}/E_{\text{peak}}$ is the isotropic photon numbers emitted per second at the characteristic photon energy defined as $E_{\text{peak}}$, which is equivalent to the ionization parameter that is widely used in the photoionization models (e.g., Osterbrock & Ferland 2006) if the densities of the ISM of different LGRBs are comparable.

For the bursts with a detection of EW of C II, one can see that there is a dependence of the C IV/C II ratio on $L_{\text{iso}}/E_{\text{peak}}$, except for two outliers with relatively large C IV/C II ratios. Generally speaking, the higher the C IV/C II ratio, the larger the $L_{\text{iso}}/E_{\text{peak}}$ will be, which indicates that the ionization ratio of the ISM around the bursts increases with the ionizing photon flux assessed from the prompt emission of LGRBs. A statistical test yields a Kendall’s $\tau = 0.238$ and a $Z$-value of 1.237 at a significance level with a probability of null correlation of $P = 0.216$. The significance of the dependence is considerably enhanced to be $\tau = 0.539$, $Z = 2.562$, and $P = 0.0104$ when the two outliers are excluded from the statistics. The significance is obviously further enhanced in the right panel of Figure 1, which plots the line ratio C IV/C II as a function of $L_{\text{iso}}/E_{\text{peak}}$. The physical meaning of $L_{\text{iso}}/E_{\text{peak}}$ can be understood as the specific photon numbers emitted per second with a photon energy of $E_{\text{peak}}$. The same statistical test results in a significantly improved statistics with a $\tau = 0.352$, $Z = 1.836$, and $P = 0.0664$ and a $\tau = 0.603$, $Z = 2.873$, and $P = 0.0041$ when the outliers are excluded.

Both C IV/C II $- L_{\text{iso}}/E_{\text{peak}}$ and C IV/C II $- L_{\text{iso}}/E_{\text{peak}}^{2}$ correlations suggest a photoionization effect in which the circum-burst medium in the line of sight is photoionized by the GRB’s prompt and afterglow emission. In fact, the photoionization effect is revealed in some previous case studies focusing on individual GRBs. A transient absorption edge at $\sim 3.8$ keV, which is produced by the circum-burst medium highly ionized by the GRB’s prompt emission, is discovered in the X-ray spectrum of the prompt emission of GRB 990705 (Amati et al. 2000). Emission features (e.g., Fe K$\alpha$ and Ly$\alpha$ lines) that resulted from photoionization by the GRB’s prompt and afterglow emission are identified in the X-ray afterglow spectra of a few GRBs (e.g., Piro et al. 1999, 2000; Yoshida et al. 1999; Antonelli et al. 2000).

The dependence of C IV/C II on $L_{\text{iso}}/E_{\text{peak}}^{2}$ shown in the right panel of Figure 1 is quite interesting. In fact, previous statistical studies firmly established a tight correlation between $L_{\text{iso}}$ and $E_{\text{peak}}$, which results in a relationship of $L_{\text{iso}} \propto E_{\text{peak}}^{2}$ in both homogeneous and wind ISM (e.g., Amati et al. 2002; Yonetoku et al. 2004; Ghirlanda et al. 2010, 2018; Nava et al. 2012). Subsequent studies suggested that the relationship is physically driven by the initial Lorentze factor (e.g., Nava et al. 2012; Ghirlanda et al. 2018 and references therein). The dependence revealed by us therefore suggests that the scatter of the $L_{\text{iso}}/E_{\text{peak}}$ ratio is related to the C IV/C II ratio.

A linear fitting FITEXY with uncertainties in both $x$ and $y$ coordinates yields a relationship of

$$\log L_{\text{iso}}/E_{\text{peak}}^{2} = (47.15 \pm 0.07) + (2.38 \pm 0.28) \log \frac{\text{C IV}}{\text{C II}}.$$  \hfill (1)

The D’Agostini fitting method (D’Agostini 2005, see also in, e.g., Guidorzi et al. 2006; Amati et al. 2008) is alternatively used to model the linear relationship as $y = \beta_0 + \beta_1 x + \epsilon$, where $\epsilon$ is the extra Gaussian scatter. The optimal values obtained by the maximum likelihood method results in a relationship

$$\log \frac{\text{C IV}}{\text{C II}} = (-12.82 \pm 2.00) + (0.27 \pm 0.04) \log \frac{L_{\text{iso}}}{E_{\text{peak}}^{2}},$$  \hfill (2) with an extra scatter of $\epsilon = 0.19$. Both best-fitted relationships are overplotted in the right panel of Figure 1.

Figure 2 shows the $E_{\text{peak}}$ versus $L_{\text{iso}}$ ($E_{\text{iso}}$) correlation for the sample used in this study. The same D’Agostini fitting method returns best fits:

$$\log E_{\text{peak}} = (-14.91 \pm 1.64) + (0.33 \pm 0.03) \log L_{\text{iso}} \quad (3)$$

associated with an extra scatter of $\epsilon = 0.32$, and

$$\log E_{\text{peak}} = (-26.13 \pm 2.86) + (0.54 \pm 0.05) \log E_{\text{iso}}, \quad (4)$$

associated with an extra scatter of $\epsilon = 0.27$. A comparison of the obtained scatters enables one to definitely see that the dispersion of the $L_{\text{iso}}/E_{\text{Peak}}^{2}$ versus photoionization ratio...
correlation is smaller than both the $E_{\text{peak}}-L_{\text{iso}}$ and $E_{\text{peak}}-E_{\text{iso}}$ correlations.

3.2. Outliers: Different Origin of LGRBs?

By including both outliers and bursts with an upper limit of EW of C II, the distribution on the C IV/C II versus $L_{\text{iso}}/E_{\text{peak}}$ ($L_{\text{iso}}/E_{\text{peak}}^2$) diagram further suggests that the bursts listed in our sample could be divided into two groups: a majority of the bursts that follow the ionization ratio versus ionizing photon flux dependence and a few outliers with either relatively large C IV/C II ratios or small $L_{\text{iso}}/E_{\text{peak}}$ ($L_{\text{iso}}/E_{\text{peak}}^2$) (or both). The three outliers in Figure 1 are GRB 050908, GRB 070411, and GRB 080810.

In the first case, Martone et al. (2017) argued that the outliers in the $E_{\text{peak}}-E_{\text{iso}}$ correlation is possibly due to an over-estimation of $E_{\text{peak}}$ that resulted from an underestimation of X-ray prompt emission. In the current sample, Figure 2, however, shows that all three outliers generally follow the fitted $E_{\text{peak}}-E_{\text{iso}}$ correlation, which suggests that the observational bias might not be a favorable explanation for the outliers.

Alternatively, the large C IV/C II ratios suggest an abnormally high ionization ratio in the ISM for the outliers. A possible explanation of the high ionization ratio is an additional photoionization contributed by the underlying intensive star formation, especially the massive Wolf–Rayet (WR) stars in the environment of the LGRBs. Taking into account the WR outflow model, Berger et al. (2006) argued that the C IV/$\lambda$1549/ Si IV/$\lambda$1403 line ratio is a good tracer of the existence of WRs because the outflow from the massive stars would increase the carbon metallicity in the ISM. In fact, a tendency of higher C IV/Si IV ratio in LGRBs than in QSOs is tentatively revealed in de Ugarte Postigo et al. (2012) through a large sample.

In order to check if the WR star scenario is working for the outliers, Figure 3 shows the cumulative distribution of C IV/Si IV ratio for the current sample. The vertical lines mark the C IV/Si IV values for the three outliers with the largest deviation from the C IV/C II versus $L_{\text{iso}}/E_{\text{peak}}$ ($L_{\text{iso}}/E_{\text{peak}}^2$) sequence. Clearly, both outliers with a firm measurement of EW of C II have quite high C IV/Si IV ratios, which agrees with the prediction of the WR scenario quite well.

The outliers with a property of both large C IV/C II and C IV/Si IV ratios motivates us to suspect that the bursts following, and deviating from, the C IV/C II–$L_{\text{iso}}/E_{\text{peak}}$ ($L_{\text{iso}}/E_{\text{peak}}^2$) sequence are produced within different environments, or, on other worlds, are produced by different progenitors. In fact, on the theoretical ground, both the single-star model with a central engine of either a black hole or a magnetar (e.g., Woosley & Heger 2006; Dai & Lu 1998; Zhang & Dai 2010; Wang et al. 2017) and close interacting binary models (e.g., Fryer et al. 2007; van den Heuvel & Yoon 2007) have been proposed as the origin of LGRBs. On the observational ground, features emitted from WR stars have been detected in the spectra of the host galaxies of eight nearby LGRBs (Han et al. 2010). With the measurements of metallicity of host galaxies of LGRBs up to $z \sim 2$, a metallicity threshold of $Z_{\text{th}} = 0.7 Z_\odot$ is suggested for the origin of LGRBs (e.g., Japelj et al. 2015; Vergani et al. 2017 and references therein). This threshold is, however, higher than the requirement of $0.2 Z_\odot$ of the single-star model, which suggests an alternative progenitor of the close interacting binary for some LGRBs, because the binary model is less sensitive to the metallicity of the progenitor.

4. Conclusion

A correlation between the line ratio C IV/C II and $L_{\text{iso}}/E_{\text{peak}}$ ($L_{\text{iso}}/E_{\text{peak}}^2$) is identified for the majority of LGRBs listed in this study, which suggests a global response of the ionization ratio to the ionizing photon luminosity assessed from the prompt emission. The outliers of the correlation, which have both high C IV/C II and C IV/Si IV ratios, motivate us to suspect that their progenitors differ from the bursts following the identified correlation.

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