OUTLIERS FROM THE MAINSTREAM: HOW A MASSIVE STAR CAN PRODUCE A GAMMA-RAY BURST

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ABSTRACT

It is now recognized that long-duration gamma-ray Bursts (GRBs) are linked to the collapse of massive stars, based on the association between (low redshift) GRBs and type Ic core-collapse supernovae (SNe). The census of massive stars and GRBs reveals, however, that not all massive stars produce a GRB. Only ~1% of core-collapse SNe are able to produce a highly relativistic collimated outflow, and hence a GRB. The extra crucial parameter has long been suspected to be metallicity and/or rotation. We find observational evidence strongly supporting that both ingredients are necessary in order to make a GRB out of a core-collapsing star. A detailed study of the absorption pattern in the X-ray spectrum of GRB 060218 reveals evidence of material highly enriched in low-atomic-number metals ejected before the SN/GRB explosion. We find that, within the current scenarios of stellar evolution, only a progenitor star characterized by a fast stellar rotation and subsolar initial metallicity could produce such a metal enrichment in its close surrounding.

Subject headings: gamma rays: bursts — stars: evolution — stars: individual (GRB 060218)

Online material: color figure

1. INTRODUCTION

The association between long GRBs and SNe hints toward Wolf-Rayet (WR) stars as GRB progenitors (Woosley & Bloom 2006; Fruchter et al. 2006). The WR phase in the evolution of a massive star is relatively short, and therefore WR stars are rarely observed. They eject high-velocity ($v_\infty \sim 1000$–2000 km s$^{-1}$), mass-loaded winds (mass-loss rates of $\dot{M} \sim 10^{-5}$ to $10^{-4}$ $M_\odot$ yr$^{-1}$) as well as massive shells during mass-loss episodes (e.g., Pastorello et al. 2007; Weiler et al. 2007). Signatures for the presence of this material can be expected in the optical light curve of GRB afterglows showing up as flux enhancements in their light curves or as (variable) fine-structure transition lines in their optical spectra. The observations of these features can set important constraints on the density and distance of the absorbing material located either in the star-forming region within which the progenitor formed, or in the circumstellar environment of the progenitor itself (Perna & Loeb 1998; Prochaska et al. 2006).

In the X-ray domain, despite the wealth of features produced by absorption of metals, relatively little progress has been achieved, mostly due to low statistics and to the relatively poor spectral resolution of the detectors. Here we consider the Swift (Gehrels et al. 2004) observations of GRB 060218. This is the second closest GRB (redshift $z = 0.033$), and the first one showing the shock break out of the SN (Campana et al. 2006). Modeling of the spectra and light curve of the associated SN 2006aj (Pian et al. 2006; Mirabal et al. 2006; Sollerman et al. 2006; Cobb et al. 2006) suggested a progenitor star whose initial mass was $20 \pm 1$ $M_\odot$ (Mazzali et al. 2006).

This GRB was of very long duration, which allowed Swift to observe it with its narrow field instruments (the X-ray Telescope, XRT [Burrows et al. 2005], and the UV/Optical Telescope, UVOT) during a considerable part of its prompt phase, collecting the largest number of X-ray photons ever. In this Letter we exploit the huge number of X-ray photons by analyzing the absorption pattern burnt into it by circumburst material.

2. X-RAY DATA ANALYSIS

The XRT spectra have been obtained in the Windowed Timing (WT) mode in which a 1D image is obtained by adding the data along the central 200 pixels in a single row (see Hill et al. 2004). The XRT data have been processed using the FTOOLS software package (ver. 6.3.1) distributed within HEASOFT. We run the task xrtpipeline (ver. 0.11.4) applying calibration and standard filtering and screening criteria. In particular, we dynamically correct for possible bias offsets computing the bias difference between the on-ground estimated bias median from the last 20 pixels data telemetered with every frame, and the median of the last 20 pixels in the related bias row. Events with grade 0 have been selected in order to attain the best spectral resolution. The XRT analysis has been performed in the 0.3–10 keV energy band (and also in the 0.35–10 keV and 0.25–10 keV energy bands as a consistency check). Given the XRT CCD resolution at low energies ($\Delta E/E \sim 15\%$) we cannot directly see the imprint of the edges in the X-ray spectrum. Rather we are sensitive to the different slopes
in between the edges leading to a precise determination of the depths of the single edges.

We extract the data from an 80 pixel wide region, given the strength of the source. The background has been extracted at the edge of the WT slit accounting for only ~0.5% of the source flux. A dedicated ARF file has been generated with the xrtmkarf task accounting for bad column holes and correcting for vignetting and point spread function losses. The latest response matrices have been used (ver. 010; see Campana et al. 2006\(^1\)). These matrices represent a big improvement with respect to the previous version. Calibration data on Mrk 421 and isolated neutron stars indicate a good response down to 0.3 keV with no apparent features and data to model ratios always below 10%. A systematic uncertainty of 2.5% has been estimated for very bright sources, at the most.

We divide the entire GRB light curve into two segments taking the XRT peak as dividing line in order to minimize the effects of spectral variations (Campana et al. 2006). This choice results in two intervals: the first 715 s (count rate 72 counts s\(^{-1}\), for a total of 51,000 photons) and the second 1907 s long (73 counts s\(^{-1}\), for a total of 139,000 photons). The peak rate is 130 counts s\(^{-1}\), well below the WT pileup limit. Data has been rebinned to have at least 100 counts per energy bin.

For the same intervals we extract survey mode BAT data (Barthelmy et al. 2005) in order to fit the XRT and BAT spectra simultaneously and better constrain the XRT high energy part of the emission model. The XRT energy range is 0.3–10 keV and the BAT range is 16–79 keV and 16–37 keV for the first and second (softer) spectrum, respectively.

The large number of counts allowed us for the first time to quantify the abundances of a number of elements, especially those absorbing at low energies. The most prominent absorption edges are those caused by carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, iron, and nickel (Morrison & McCammon 1983). We considered a simple absorption model including absorption by gas in our Galaxy and intrinsic absorption in the host galaxy (at the known redshift, both modeled with tbabs [Wilms et al. 2000], and the standard XSPEC abundance pattern [Anders & Grevesse 1989]) folding a blackbody plus a cutoff power-law emission model (the soft component is mandatory to obtain a good fit at variance with most GRBs; Campana et al. 2006). The Galactic absorption has been left free to vary within the interval (9.8–15) \(\times 10^{21}\) cm\(^2\). This has been estimated by accumulating 360 ks over the field of

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**Table 1**

| Model | Energy Range (keV) | Gain | Systematic Uncertainty (2.5%) | \(\chi^2_{\nu}\) | F-Test\(^a\) |
|-------|-------------------|------|-------------------------------|---------------|-----------|
| 1'     | 0.25–10           | No   | No                            | 1.11 (830) [0.01] | ...       |
| 2'     | 0.30–10           | No   | No                            | 1.10 (827) [0.02] | ...       |
| 3'     | 0.35–10           | No   | No                            | 1.10 (825) [0.02] | ...       |
| 4'     | 0.3–10            | Yes  | No                            | 1.07 (825) [0.06] | 5.5       |
| 5'     | 0.3–10            | Yes  | Yes                           | 0.96 (825) [81] | 5.1       |

\(^{a}\) dof: Degrees of freedom; nhp: null hypothesis probability.

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\(^{1}\) See also http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/docs/xrt/SWIFT-XRT-CALDB-09.
X-ray absorption is frequently observed in GRB afterglows (Galama & Wijers 2001; Stratta et al. 2005; Watson et al. 2007), even when adopting the dust-to-gas ratio of the Small Magellanic Cloud (SMC; Pei et al. 1992).

Despite the large number of counts, we do not have enough sensitivity to leave free the abundances of all individual elements in the fitting procedure. We focus therefore on the CNO abundances (with absorption edges at rest-frame energies of 0.28, 0.41, and 0.54 keV, respectively) as additional free parameters, while we adopt the abundances derived from optical studies for the remaining elements (see Table 2). The CNO abundances are (much) larger than the solar value. Fitting for a gain offset further improves the fit with values in the −30 to −10 eV range. With this model we obtain a better fit to the data with an F-test probability of 5.1–5.5 σ (depending on the adopted systematic uncertainties in the response matrix). The host galaxy column density is in this case \( N_{H1} = 1.1^{+0.9}_{-0.4} \times 10^{20} \text{ cm}^{-2} \), which is consistent with the optical absorption measured in the host galaxy for an SMC dust to gas ratio. This result may indicate that the discrepancy between optical and X-ray absorption is simply due to a large amount of circumburst material enriched in CNO elements. If these are mostly in the form of gas then they cause absorption in the X-rays but not in the optical.

The error on the CNO abundances has been evaluated with the steppar command within XSPEC to circumvent non-monotonicity in \( x^2 \) space. We also tried a different absorption model using varabs within XSPEC, obtaining very similar results.

An additional issue could be the rapidly evolving spectrum, leading to spurious spectral features. To test whether this could pose a problem, we divide the two initial spectra into six smaller intervals each. We generate the appropriate response and then fit with the same model as above (and absorption parameters fixed) the resulting spectra. Then, we simulate spectra with a factor of 10 more photons and join them. The two resulting fake spectra recover quite well the initial absorption pattern (now left free to vary) within the fitting uncertainties.

GRB 060218 occurred in 2006 February. Data has been processed with the appropriate version 6 gain files (swxwtgains0_20010101v006.fits, calibrated in 2005). As a test, we also used version 7 of the gain file (swxwtgains0_20010101v007.fits, calibrated in late 2006–2007). This new gain file together with a new ARF file (yet unreleased) provides a superior description of the spectral models but it is fully appropriate for observations taking place nowadays. We reprocess all the data and fit them with the same best-fit model. We check that also in this case we obtain the same results well within the uncertainties and, more importantly, the same ratios by number. This positive test further strengthens our observational result.

### TABLE 2

| Element | Edge Energy (keV) | Rest Frame & Solar Abundance (Ref. | Column Density (cm⁻²) |
|---------|------------------|-----------------------------------|------------------------|
| C       | 0.268            | 0.277 3.6 \times 10⁻³ 15^{+0.05}_{-0.05} | 6^{+10}_{-9} \times 10⁹ |
| N       | 0.380            | 0.392 1.1 \times 10⁻³ 52^{+0.05}_{-0.05}2 | 7^{+2}_{-3} \times 10⁹ |
| O       | 0.508            | 0.525 8.3 \times 10⁻³ 2.2^{+0.05}_{-0.05} | 2^{+0.2}_{-0.3} \times 10⁹ |

3. DISCUSSION AND CONCLUSIONS

Since we do not have a knowledge of the total mass involved, the most insightful measurement we obtain from X-ray best-fit data is the ratio by number of the abundances of C, N, and O. We derive C/N = 0.9^{+0.7}_{-0.5} and O/N = 0.3^{+0.7}_{-0.5} (or logarithmic abundances relative to the solar value [C/N] = −0.5^{+0.5}_{-0.3} and [O/N] = −1.4^{+0.5}_{-0.3}). This extremely low O/N ratio is very difficult to account for in terms of standard interstellar medium and of stellar evolution models of isolated stars. In particular, solar metallicity models are unable to reproduce these abundance ratios (Hirschi et al. 2005; Portinari et al. 1998). Possibly, binary evolutionary models can account for this constraint more easily, having more degrees of freedom, but recent models seem to indicate that conditions similar to single star progenitors are needed (Detmers et al. 2008).

A key ingredient in the evolution of single massive stars is missing: rotation-induced mixing in the stellar interior. If the ejected mass reflects the C/N and O/N ratios that would be expected at the end of the main-sequence phase as observed in several nebulae around bright stars, we would need a large rotation-induced mixing fraction with only ~10% of the initial mass unprocessed (based on calculations in Lamers et al. 2001). This mixing can occur only in the case of a very fast stellar rotation (close to breakup). A viable alternative could also be provided by a close binary system, either in terms of tidal locking or evolution through a common-envelope phase during which an enriched shell might be ejected.

The collapsar scenario requires massive helium stars with rapidly rotating cores to produce a GRB (Woosley 1993; MacFadyen & Woosley 1999). However, stellar models with magnetic torques fail to retain such high core angular momentum. In the last few years there has been mounting theoretical support for the idea that only massive stars that are initially very rapidly rotating and have sufficiently low metallicities can satisfy the conditions for GRB formation (Yoon & Langer 2005; Woosley & Heger 2006). In fact, below a suitable metallicity threshold, a rotationally induced mixing process produces a quasi-chemically homogeneous stellar evolution avoiding the spin-down of the stellar core. As a test bed we consider massive star evolution models at subsolar initial metallicities (Yoon et al. 2006). We also limit the mass range of the progenitor to 15–25 \( M_\odot \), according to the detailed modeling of the supernova ejecta (Mazzali et al. 2006). We find that a number of models are able to satisfy our constraints (see Fig. 2). All these models are characterized by a fast semiconvective mixing of the core. Within the initial mass range of the progenitor we are able to constrain the initial fraction of the Keplerian velocity (\( v_\text{K} \)) of the equatorial rotational velocity to 0.45 ≤ \( v_\text{K} \)/\( v_\odot \) ≤ 0.8 and the initial metallicity to \( Z < 0.1 Z_\odot \). With these parameters the progenitor star fits nicely within the allowed region for the GRB production (Yoon et al. 2006). It thus appears that the observations of GRB 060218 provide the first observational evidence that only a progenitor star characterized by a fast stellar rotation and subsolar initial metallicity can lead to such an explosive event.

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Fig. 2.—Constraints from the abundance ratio in the plane of initial mass and initial stellar velocity (in units of equatorial Keplerian velocity) as described in Yoon et al. (2006). The four panels refer to four different initial metallicities (0.2, 0.1, 0.05, 0.0005 $Z_{\odot}$, clockwise). We note that the mean host galaxy metallicity has been estimated as $Z \sim 0.07 Z_{\odot}$. Different final end products can be identified in this plane for rotating single massive stars. The solid line divides the plane into two parts, where stars evolve quasi-chemically homogeneous above the line, while they evolve into the classical core-envelope structure below the line. The dot-dashed lines bracket the region of quasi-homogeneous evolution where the core mass, core spin, and stellar radius are compatible with the collapsar model for GRB production (absent at $Z = 0.2 Z_{\odot}$). The GRB production region is divided into two parts, where GRB progenitors are WN or WC/WO types. The dashed line in the region of non-homogeneous evolution separates Type II supernovae (SN II; left) and black hole (BH; right) formation, where the minimum mass for BH formation is simply assumed to be $30 M_{\odot}$. We added to these planes single star models allowed by the abundance constraints derived from the X-ray spectrum of GRB 060218. Filled circles represent single star models from Yoon et al. (2006) which satisfy the abundance constraints derived from X-ray data; open circles represent instead models not satisfying these constraints. Larger dots refer to models within the 15–25 $M_{\odot}$ (initial) progenitor mass range (i.e., within the vertical strip), based the mass estimate from Mazzali et al. (2006).

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