No supernovae detected in two long-duration Gamma-Ray Bursts

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There is strong evidence that long duration gamma-ray bursts (GRBs) are produced during the collapse of a massive star. In the standard version of the Collapsar model, a broad-lined and luminous Type Ic core-collapse supernova (SN) accompanies the GRB. This association has been confirmed in observations of several nearby GRBs. Recent observations show that some long duration GRBs are different. No SN emission accompanied the long duration GRBs 060505 and 060614 down to limits fainter than any known Type Ic SN and hundreds of times fainter than the archetypal SN 1998bw that accompanied GRB 980425. Multi-band observations of the early afterglows, as well as spectroscopy of the host galaxies, exclude the possibility of significant dust obscuration. Furthermore, the bursts originated in star-forming galaxies, and in the case of GRB 060505 the burst was localised to a compact star-forming knot in a spiral arm of its host galaxy. We find that the properties of the host galaxies, the long duration of the bursts and, in the case of GRB 060505 the location of the burst within its host, all imply a massive stellar origin. The absence of a SN to such deep limits therefore suggests a new phenomenological type of massive stellar death.

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1. Introduction

The collapse of massive stars on some occasions produce long duration \(\gamma\)-ray bursts (GRBs). It was a common expectation that broad-lined and luminous Type Ic core-collapse supernova (SN) accompany every long-duration GRB (Zeh et al. 2004; Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Malesani et al. 2004; Pian et al. 2006), though it was not clear that such an expectation was justified on theoretical grounds.

The GRBs 060505 and 060614 were detected by (the dedicated GRB satellite) \textit{Swift}'s \(\gamma\)-ray Burst Alert Telescope (BAT) on 2006 May 5.275 and 2006 June 14.530 respectively (Hullinger et al. 2006; Parsons et al. 2006). GRB 060505 was a faint burst with a duration of 4 s. GRB 060614 had a duration of 102 s and a pronounced hard to soft evolution. Both were rapidly localised by \textit{Swift}'s X-ray telescope (XRT). Subsequent follow-up of these bursts led to the discovery of their optical afterglows, locating them in galaxies at low redshift: GRB 060505 at \(z = 0.08913\) (Fynbo et al. 2006) and GRB 060614 at \(z = 0.12514\) (Della Valle et al. 2006). The relative proximity of these bursts engendered an expectation that a
bright SN would be discovered a few days after the burst, as had been found before in other low-redshift long duration GRBs.

2. Observations and results

We monitored the afterglows of GRB 060505 and 060614 at optical/near-infrared wavelengths. This led to early detections of the afterglows. We continued the monitoring campaign and obtained stringent upper limits on any re-brightening at the position of the optical afterglows up to 12 and 5 weeks after the bursts, respectively. The light-curves obtained based on this monitoring are shown in figure 1.

For GRB 060505 we detected the optical afterglow at a single epoch in multiple bands ($B$, $V$, $R$ and $I$, Xu et al. in preparation). All subsequent observations resulted in deep upper limits. For GRB 060614 we followed the decay of the optical afterglow in the R-band up to four nights after the burst. No source was detected to deep limits at later times. As seen in figure 1, the upper limits are far below the fluxes of previous Ic SNe, in particular SNe associated with long GRBs (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Malesani et al. 2004; Pian et al. 2006). For both GRBs our 3σ limit around the time of expected maximum of a SN component is 80–100 times fainter than SN 1998bw. The very deep observations of GRB 060505 on May 23 and May 30 give a 3σ upper limit more than 250 times fainter than SN 1998bw at a similar time. Hence, any SN associated with GRB 060505 must have had a peak magnitude in the $R$-band fainter than about $-13.5$.

These two SN-less GRBs share no obvious characteristics in their prompt emission. GRB 060505 was one of the least luminous bursts discovered with Swift with an isotropic-equivalent energy release of $1.2 \times 10^{49}$ erg. It had a relatively short duration, and was single-peaked with a very faint afterglow. GRB 060614 was about a hundred times more luminous with an isotropic-equivalent energy release of $8.9 \times 10^{50}$ erg, and it showed strong spectral evolution. Its optical afterglow brightened for the first day (Schmidt et al. 2006), reminiscent of GRB 970508 (Pedersen et al. 1998).

(a) Low extinction

An obvious explanation to explore for the absence of a SN is the presence of dust along the line of sight. In these cases however, we are fortunate that the levels of Galactic extinction in both directions are very low, $E(B-V)=0.0216$ mag. In the case of GRB 060505, our spatially resolved spectroscopy of the host galaxy allows us to use the Balmer emission line ratios to limit the dust obscuration at the location of the burst. The Balmer line ratio is consistent with no internal reddening. In the case of GRB 060614, the detection of the early afterglow in many bands, including the Swift UV bands UVW1 and UVW2 (Holland 2006), rules out significant obscuration of the source in the host galaxy and we conclude that there is no significant dust obscuration in either case (see also Della Valle et al. 2006).

(b) Host galaxies

Both GRBs were located in star-forming galaxies. The host galaxy of GRB 060505 has an absolute magnitude of about $M_B = -19.6$ and the spectrum displays the
prominent emission lines typically seen in star-forming galaxies. The 2-dimensional spectrum shows that the host galaxy emission seen at the position of the afterglow is due to a compact H\textsc{ii} region in a spiral arm of the host (see figure 2 and Thöne et al. in prep.). We estimate a star-formation rate (SFR) of 1 M\textsubscript{⊙} yr\textsuperscript{-1} and a specific SFR of about 4 M\textsubscript{⊙} yr\textsuperscript{-1} \( (L/L^*)^{-1} \) (assuming \( M^*_{B} = -21 \)).

The host galaxy of GRB 060614 is significantly fainter than the host of GRB 060505, with an absolute magnitude of about \( M_{B} = -15.3 \). This is one of the least luminous GRB host galaxies ever detected. GRB 060614 was observed with the GMOS imaging spectrometer on the Gemini 8-m on the night of 29 July 2006. We detected the H and \([\text{O} \text{iii}]\) emission lines and infer an SFR of 0.014 M\textsubscript{⊙} yr\textsuperscript{-1}. The specific SFR is 3 M\textsubscript{⊙} yr\textsuperscript{-1} \( (L/L^*)^{-1} \).

Sub-L\textsuperscript{*}, star-forming host galaxies, like these two, are fairly common among long GRB host galaxies (Fruchter et al. 2006). For comparison, the specific SFRs of the 4 previously studied nearby \( (z < 0.2) \) long GRB host galaxies are 6, 7, 25 and 39 M\textsubscript{⊙} yr\textsuperscript{-1} \( (L/L^*)^{-1} \) (Sollerman et al. 2005, 2006). Hence, the specific SFRs of the two hosts studied here are slightly lower than the four previously studied nearby hosts, but the scatter in the rates is large and it is not possible to conclude that the host galaxies of GRB 060505 and GRB 060614 are qualitatively different from other \( z < 0.2 \) long-GRB host galaxies.

\begin{figure} [h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Optical afterglow light-curves of two nearby \( \gamma \)-ray bursts: a) GRB 060505 and b) GRB 060614. The light-curves of the Ic SNe 1998bw, 2002ap and 2006aj, are plotted as they would have appeared at the redshift of GRB 060505 (a, left) and at the redshift of GRB 060614 (b, right). Afterglow detections (black, filled circles) and subsequent 3\( \sigma \) upper limits are plotted. We conclude that neither GRB 060505 nor GRB 060614 were associated with significant SN emission down to very faint limits hundreds of times less luminous than the archetypal SN 1998bw. For GRB 060614 the early light-curve data is taken from Holland (2006) (open circles).}
\end{figure}

Figure 2. VLT images and spectra of the GRB 060505 host galaxy. a) The field (24″ × 24″) of GRB 060505 as observed from the VLT in the R-band on Sep 14. The arrow marks the position where the optical afterglow was detected. The source seen at this position in the image is a compact star-forming region in which the progenitor of GRB 060505 was located. b) The result of subtracting the Sep 14 image seen in a from the May 6 image. Seen is the optical afterglow component alone. c) As (a), but with the position of the optical afterglow marked with red contours and with the orientation of the slit for the May 23 spectrum indicated. The position of the afterglow is within the astrometric uncertainty of less than 0.05″ coincident with the position of the compact star-forming region. d) The 2-dimensional optical spectrum obtained with VLT/FORS2 on May 23. As seen in (c) the slit covered the centre of the host galaxy and the location of GRB 060505. As seen in the spectrum, this site is indeed a bright star-forming region in the host galaxy and we hence have very strong evidence that the 060505 progenitor was a massive star. From the ratio of the Balmer line strengths we exclude dust extinction of more than a few tenths of a magnitude in the R-band. e) Spectra of the host galaxy (upper pane) and star-formation knot (lower pane) associated with GRB 060505. Hydrogen and oxygen lines associated with star-formation are clearly detected. Insets: Hα and [Nii]. The ratio of [Nii] λ/Hα is smaller in the spectrum of the progenitor site, implying a lower metallicity and/or a more intense ionising flux here than in the host as a whole.
3. Could GRB 060505 and GRB 060614 be short GRBs or at higher redshifts?

The duration of the prompt emission GRB 060505 and GRB 060614 is 4 s and 102 s, respectively. Hence, they are both well outside the classification of short bursts, i.e. duration less than 2 s (Kouveliotou et al. 1993). It is worth noting in this context that the typical long GRBs 000301C at $z = 2.04$ and 020602 at $z = 4.05$ had durations of only 2 s and 7 s, respectively, so their rest-frame durations are significantly shorter than the 4 s of even GRB 060505. Short GRBs have previously had accompanying SNe excluded (Hjorth et al. 2005a; Bloom et al. 2006). Therefore, it might be speculated that both SN-less GRBs studied here were extreme members of the class of progenitors responsible for short GRBs. Short GRBs have in some cases been found to be associated with older stellar populations than long GRBs, and it is widely expected that they are predominantly caused by merging compact objects (Gehrels et al. 2005).

In addition to their long duration, the facts that 1) GRB 060505 and GRB 060614 can be localized to star-forming galaxies, 2) in the case of GRB 060505 even a star-forming region in a spiral arm of its host galaxy (see figure 2), and 3) in the case of GRB 060614 the afterglow is located around the half-light radius of its star-forming host (Gal-Yam et al. 2006) all strongly suggest that the progenitors were massive stars. The evidence in this paper should cause us to be more open-minded about the origins of short GRBs: absence of SNe has been an argument used to support the idea that short GRBs do not have a massive stellar progenitor. Now we have observed long-duration SN-less GRBs in star-forming regions, suggesting that a non-detection of a SN does not preclude a massive progenitor. In the near future, the location of the GRB, i.e. in a star-forming region or in an older component, may be the only way to discriminate between merging compact objects and massive stars as progenitors. In fact, several host galaxies for short GRBs have been found to be as actively star-forming as some host galaxies of long GRBs (Hjorth et al. 2005b; Soderberg et al. 2006). The GRB labels ‘long’ and ‘short’ have become synonymous with ‘massive stars’ and ‘other progenitors’. These distinctions may need to be relaxed.

It has also been suggested that GRB 060505 and GRB 060614 could in fact be more distant bursts and that the proposed hosts are only foreground galaxies. In the case of GRB 060505, it is very unlikely that the afterglow is superposed precisely on a star-forming knot in the spiral arm of a foreground galaxy (figure 2) if it was in fact more distant. In the case of GRB 060614 the impact parameter is about 0.5", and the afterglow is located around the half-light radius of the proposed host galaxy (Gal-Yam et al. 2006). The Swift-UVOT detection of the afterglow (Holland 2006) places an upper limit on the redshift of about $z \sim 1$. At such relatively low redshift the host galaxy should be detectable in the very deep HST images of the field, but no other galaxy than the proposed host galaxy is seen (Gal-Yam et al. 2006). Furthermore, even at $z \sim 1.1$, any SN would still have to be $\gtrsim 2$ magnitudes fainter than SN 1998bw to remain undetected. Therefore, it is very unlikely that either GRB 060505 or GRB 060614 are at higher redshifts than $z = 0.089$ and $z = 0.125$, respectively.
4. No detected SNe

All spectroscopically confirmed SN-GRBs have peak magnitudes within about half a magnitude of SN 1998bw [Zeh et al. 2004; Woosley & Bloom 2006]. For X-ray Flashes (XRFs) there has been some evidence that associated SNe may span a somewhat wider range of luminosities [Pian et al. 2006; Levan et al. 2005; Soderberg et al. 2005; Fynbo et al. 2004], but still well within the range of non-GRB-selected Type Ic SNe. Any SN associated with these two long GRBs must therefore have been substantially fainter than any SN Ic seen to date. Scaling the peak magnitude of a type Ic SN with the ejected $^{56}$Ni mass suggests that the mass of $^{56}$Ni ejected in these cases is less than one percent of a solar mass.

The non-appearance of a SN in these cases was a surprise and indicates that we have uncovered GRBs with quite different properties from those studied previously. It is plausible that the origin of these bursts lies in one of the many SN-less GRB progenitors suggested prior to the definitive association between GRBs and SNe. We note, however, that our results confirm a prediction within the Collapsar model: that while direct black hole (BH) formation is likely to result in SNe associated with GRBs, ‘fallback’-formed BHs could produce SN-less GRBs [Fryer et al. 2006; Heger et al. 2003; Nomoto et al. 2005]. These authors cited immediately above argue that the nucleosynthetic yields from the explosion related to the fallback-formed BH are very different from those resulting from a direct-formed BH. In the fallback case, little $^{56}$Ni is synthesized and expelled, resulting in the prediction that only very faint SNe, perhaps hundreds of times fainter than SN 1998bw, should be observed in some GRBs. Among core collapse SNe, a few very nickel deficient [Sollerman et al. 1998] and low velocity [Zampieri et al. 2003] type II SNe have been detected that were explained using this fallback mechanism [Pastorello et al. 2004, see also]. It has been pointed out that given the relatively less massive progenitors, fallback BH formation should also be relatively common among (Collapsar) GRBs. In another variant of the Collapsar model, progenitor stars with relatively low angular momentum could produce SN-less GRBs [MacFadyen 2003].

That some massive stars explode with a SN expelling large amounts of nucleosynthesised gas at high velocities, while other massive stars die with a whisper, clearly has consequences for our understanding of the energy input and the metal enrichment to the interstellar medium. Until the era of gravitational wave detectors [van Putten et al. 2004] or more sensitive neutrino astronomy [Hughes et al. 2005], it seems that GRBs will be the only signals we get from the deaths of some massive stars. Of the six long GRBs or XRFs known to be at low redshift ($z < 0.2$), two now have no associated SN, so the fraction of SN-less GRBs could be substantial.

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