THE SPECTRAL LAG OF GRB 060505: A LIKELY MEMBER OF THE LONG-DURATION CLASS

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ABSTRACT

Two long \( \gamma \)-ray bursts, GRB 060505 and GRB 060614, occurred in nearby galaxies at redshifts of 0.089 and 0.125, respectively. Due to their proximity and durations, deep follow-up campaigns to search for supernovae (SNe) were initiated. However, none were found in either case, to limits more than 2 orders of magnitude fainter than the prototypical GRB-associated SN, 1998bw. It was suggested that the bursts, in spite of their durations (\( \sim 4 \) and \( \sim 102 \) s), belonged to the population of short GRBs which has been shown to be unrelated to SNe. In the case of GRB 060505 this argument was based on a number of indicators, including the negligible spectral lag, which is consistent with that of short bursts. GRB 060505 has a shorter duration, but no spectral lag was measured. We present the spectral lag measurements of GRB 060505 using Suzaku’s Wide Area Monitor and the Swift Burst Alert Telescope. We find that the lag is \( 0.36 \pm 0.05 \) s, inconsistent with the lags of short bursts and consistent with the properties of long bursts and SN GRBs. These results support the association of GRB 060505 with other low-luminosity GRBs also found in star-forming galaxies and indicate that at least some massive stars may die without bright SNe.

Subject heading: gamma rays: bursts

1. INTRODUCTION

The existence of two classes of gamma-ray bursts (GRBs) differing in observed durations and spectral properties has been established for some time (e.g., Mazets et al. 1981; Norris et al. 1984; Hurley 1992). These populations were quantified using the Burst and Transient Source Experiment (BATSE), which showed a bimodal distribution in the durations of GRBs. Well fit by two lognormal functions (McBreen et al. 1994), with the divide at \( \sim 2 \) s (Kouveliotou et al. 1993). In addition, there is also contamination in the short-burst class from soft gamma-ray repeaters (e.g., Chapman et al. 2008). It is generally accepted that long GRBs have their origins in massive star progenitors because of their association with core-collapse supernovae (SNe; Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Malesani et al. 2004; Pian et al. 2006; Woosley & Bloom 2006) and occurrence in star-forming galaxies (Bloom et al. 2002) and in highly star-forming regions therein (Fruchter et al. 2006). The origin of short GRBs is still open, with mergers of compact objects being the leading concept (e.g., Gehrels et al. 2005; Hjorth et al. 2005; Fox et al. 2005).

The detection of the spectroscopic signatures of SNe in the four nearest GRBs and the detection of bumps consistent with SNe in the light curves of most low-redshift bursts seemed to confirm the paradigm that all long GRBs would be associated with SNe (Zeh et al. 2004; Woosley & Bloom 2006), as predicted by the collapsar model of long GRBs (Woosley & MacFadyen 1999). Doubts were cast on this paradigm by the nondetection of SNe in two nearby GRBs, GRB 060505 at \( z = 0.089 \) (Ofek et al. 2006) and GRB 060614 at \( z = 0.125 \) (Price et al. 2006) discovered by the Swift (Gehrels et al. 2004) Burst Alert Telescope (BAT; Barthelmy 2005). Due to their long durations, \( T_{90} \) of \( 4 \pm 1 \) s and \( 102 \pm 5 \) s, respectively (Hullinger et al. 2006; Barthelmy et al. 2006), SN searches were initiated. Although a supernova \( \sim 100 \) times fainter than SN 1998bw would have been detected, none was found in either case (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006; Ofek et al. 2007). It was suggested that they were short bursts where the lack of SNe would not be surprising, as short GRBs have not shown SN emission (Hjorth et al. 2005; Fox et al. 2005; Bloom et al. 2006; Covino et al. 2006).

The classification of GRBs with durations close to the long/short division is problematic. The argument that GRB 060614 was a “short GRB” rests on its extended soft emission component and on its negligible spectral lag (Gehrels et al. 2006; Zhang et al. 2007). When the latter is combined with its relatively low luminosity, it violates the lag-luminosity relation found by Norris et al. (2000) for long GRBs. If the lack of a SN in GRB 060505 is to be attributed to it being a short burst, it should also have a negligible lag. We present the spectral lag analysis of the prompt emission of GRB 060505 using data from the Suzaku Wide Area Monitor (WAM) and Swift BAT.

2. OBSERVATIONS AND DATA REDUCTION

GRB 060505 was detected by the BAT instrument on Swift. The fluence is \( (6.2 \pm 1.1) \times 10^{-7} \) ergs cm\(^{-2} \) (15–150 keV) and the spectrum is fit by a power law with index 1.3 \( \pm 0.3 \) (Hullinger et al. 2006). The trigger fell below the 6.5 \( \sigma \) threshold for an automatic slew but ground analysis found an 8.5 \( \sigma \) excess (Palmer et al. 2006). Swift was repointed at \( T_{90} + 0.6 \) days and a weak fading X-ray source was identified (Conconi et al. 2006). We obtained the publicly available data for GRB 060505 from the Swift archive.\(^7\) A mask-weighted light curve
was generated using the BAT data analysis tools. The available data contained only 10 s of event data and the light curve is presented in Figure 1. **Swift** was approaching the South Atlantic Anomaly when the burst occurred and was subject to a higher than normal background level. In addition, the partial coding was only 11% (Hullinger et al. 2006) meaning that the off-axis angle with respect to the **Swift** axis was almost 50°, substantially reducing the effective area of the instrument. Splitting the data into energy channels for spectral lag analysis further reduces the weak signal.

The WAM is the anticoincidence shield (ACS) of the Hard X-ray Detector on **Suzaku** (Yamaoka et al. 2006a) and it also triggered on GRB 060505. The WAM consists of four identical walls which act as individual detectors (WAM0 to WAM3). The detectors have a large effective area (Yamaoka et al. 2006a). They are sensitive in the energy range 50–5000 keV, and although its primary role is to act as an ACS, WAM is also used as an all-sky monitor for GRBs. An automated triggering system operates on board (Yamaoka et al. 2006b) and the light curves are publicly available at 15.6 ms resolution in four rough energy bands 50–110, 110–240, 240–520, and 520–5000 keV. The light curves in the four energy channels from the WAM0 detector at 100 ms resolution are presented in Figure 1. The $T_{90}$ of GRB 060505 was $\sim$4.8 s in the 50–5000 keV band (see footnote 8). The burst struck the WAM detector at an angle such that principally WAM0, but also to a lesser extent WAM3, detected the burst. The on-axis effective area of the BAT and WAM instruments are shown in Figure 2 of Yamaoka et al. (2006a) and the effective area of WAM only exceeds that of BAT above 300 keV. However, it should be remembered that GRB 060505 occurred $\sim$50° off-axis in BAT and that the effective area of BAT also drops rapidly above 100 keV. These factors result in a more significant detection of GRB 060505 by WAM than BAT and we therefore we rely primarily on the WAM data for our analysis. However, we show that the results are consistent with those obtained from the BAT data.

### 3. DATA ANALYSIS AND RESULTS

The spectral lag was calculated by cross-correlating the light curves in different energy channels (e.g., Band 1997; Norris et al. 2000a; Foley et al. 2008). The cross-correlation function (CCF) was fit with a fourth-order polynomial and the quoted lag value is the peak of this function. Statistical errors were calculated using a bootstrap method as described in Norris et al. (2000a). This involves adding Poissonian noise based on the observed counts to the light curves in the different energy channels and recomputing the CCF in 100 realizations for each burst. The 50th ranked value is the mean lag and the 16th and 84th ranked values represent ± 1 $\sigma$.

The spectral lag was determined between the 50–110 and 110–240 keV ($t_{10,110}$) energy bands for the **Suzaku** WAM detectors over a range of temporal resolutions (15.6, 31.2, 46.8, 62.4, 78, and 100 ms). The light curves were correlated from −4 to +4 s and the CCF was fit over a range of $\sim$5 s. A light curve threshold of 10% (30%) is applied, which means that only data with at least one-tenth (three-tenths) of the peak count rate is used to calculate the lag, thus reducing the background. The spectral lag values obtained from WAM0 at the six time resolutions specified above at 10% threshold agree within 10% of the average value. Above the 50% threshold the results are unreliable and the lag is not accurately reproduced. The burst is detected with lower significance in WAM3 and does not allow an accurate determination of the lag. We add the signal from WAM3 to that of WAM0 to test whether this gives a consistent result. The results are consistent with WAM0 alone within $\sim$1 $\sigma$, except at 100 ms resolution where the WAM0+3 lag is larger but is consistent at $\sim$3 $\sigma$ with the WAM0 results (10% threshold). The average value obtained from the sum of the WAM0 and WAM3 light curves is 0.42 ± 0.05 s at 10% and 30% thresholds, respectively. The cross-correlation data and fit for WAM0 at 100 ms is presented in Figure 2a and is inconsistent with the negligible lag expected for a short burst. A precursor is evident in the WAM data at $\sim$8 s and including it in the lag analysis over a wider time range results in a consistent lag measurement of 0.47 ± 0.06 s. We note that precursors are not normally detected in short bursts.

The lag was also measured between the 25–50 keV and 50–100 keV energy bands ($t_{50,100,25–50}$) at 100 ms using the BAT data with the techniques outlined above (Fig. 2b). The light
clearly inconsistent with zero lag. The vertical lines denote zero lag. The spectral lag value of 0.4 ± 0.1 s measured using the BAT data is consistent within 1σ with that obtained from the WAM0 and WAM0+3.

In order to establish the robustness of our result, we determined the lag for 16 additional GRBs detected by both BAT and WAM, for which the light curve data were sufficient for lag analysis in both instruments. The analysis was performed in a similar manner to GRB 060505. The derived lags ranged from −3 ms to 0.94 s in the WAM0 and 0 to 0.86 s in the BAT. The lags are compatible considering the differing instruments and off-axis angles, energy ranges, and the spectra of the bursts, except in two cases where the BAT lag was significantly longer. The sample consisted of 12 long and four short bursts. Crucially, the short bursts were always found to have negligible lag in both instruments. This shows that our analysis is sensitive to short lags.

4. DISCUSSION

4.1. Spectral Lags

The spectral lags in GRBs have been discussed by many authors (e.g., Band 1997; Norris et al. 2000a, 2000b; Norris & Bonnell 2006; Hakkila & Giblin 2006; Hakkila et al. 2007; Foley et al. 2008). Using BATSE data, Norris (2002) and Norris & Bonnell (2006) found that long-duration GRBs had both measurable and zero lags but that short GRBs had lags around zero. Norris & Bonnell (2006) calculated the lags of 260 short GRBs using BATSE data and found that 90%–95% of the values were consistent with zero and suggest that bursts with positive lag may result from contamination by the long GRB class. It was also argued that if short GRBs had lags proportionally as large as long GRBs, such lags would be detectable, i.e., that this result was not simply an effect of the duration of short bursts. This is not to say that bursts with short lags are necessarily in the short GRB class. In the sample of published lags of BATSE data by Hakkila et al. (2007) 1427 bursts have $T_{90} ≥ 2$ s and a measured lag ($τ_{(100–50,20–50)}$) of these bursts 214 have lags in the range from −10 to +10 ms (79 with uncertainties of ±10 ms) and 348 have lags in the range from −20 to +20 ms (217 with uncertainties of ±20 ms), showing that there are many long GRBs with very short lag. In summary, long bursts are expected to have predominantly positive lags ranging from zero to several seconds. Short GRBs have almost exclusively negligible lags. However, it is not possible to exclude that GRB 060505 could be an outlier, i.e., a short duration GRB with a positive lag or due to a process which does not fit into the lag classification scheme.

There have been difficulties in classifying a number of bursts and the lag has been used to discriminate in a number of cases (e.g., Donaghy et al. 2006). For example, GRB 060912A has a $T_{90}$ of ~6 s and was initially thought to have occurred in a nearby elliptical galaxy; however, Levan et al. (2007) recently found that it was more likely to come from a star-forming galaxy at $z = 0.937$ and report a lag ($τ_{(100–50,20–50)}$) of 83 ± 43 ms. Various strategies have been proposed to distinguish bursts more effectively than the duration alone (e.g., Norris et al. 2000a; Donaghy et al. 2006; Zhang et al. 2007). However, none have seen widespread adoption.

4.2. What Was the Progenitor of GRB 060505?

It was argued that GRB 060505 was probably part of the tail of the short-burst population and connected to mergers of compact objects. At a redshift of $z = 0.089$, GRB 060505 has an isotropic peak luminosity of ~$9 \times 10^{52}$ ergs s$^{-1}$ (50–300 keV). Having a low luminosity and relatively long lag of 0.36 ± 0.05 s, GRB 060505 falls below the lag-luminosity relation of Norris et al. (2000a) as shown in Figure 3. The spectral lag of GRB 060505 is significantly longer than those measured for short GRBs and GRB 060614 and it falls on the lag-luminosity plot in a position similar to that of some (but not all) SN GRBs (e.g., GRB 031203).

Ofek et al. (2007) argue that the simplest interpretation for GRB 060505 is that it is related to a merger event rather than a short-lived massive star and point out that the maximum allowable distance of GRB 060505 from a star-forming knot is consistent with the shortest merger timescales. Thöne et al. (2008) claim that GRB 060505 occurred in a star-forming region of the host galaxy which resembles long GRB host galaxies and argue for a massive star origin for this event. It has also been argued that the host galaxy of GRB 060505 is more similar a short burst host in terms of metallicity and ionization state (Levesque & Kewley 2007). However, their short GRB host region in the emission-line-ratio diagram is based on only two burst host galaxies, one of which is GRB 050416A, which has photometric evidence for an associated SN (Soderberg et al. 2007) and is argued to be a long GRB due its spectral
softness and location on the Amati plot (Sakamoto et al. 2006). The host-galaxy studies alone do not resolve the classification issue for GRB 060505. The optical luminosity at 12 h in the source frame is similar to those of short GRB afterglows, but optical luminosity alone is not also a valid classification tool (D. A. Kann et al. 2008, in preparation). In our opinion, the lag measurement suggests that this burst is similar to long GRBs implying a massive star progenitor, despite the lack of a SN detection.

It has been argued that the absence of a SN signature in GRB 060505 is evidence of a new, quiet endpoint for some massive stars (Fynbo et al. 2006; Watson et al. 2007). The existence of a SN was a feature of the early collapsar model. However, the complete absence of a SN may be expected where the $^{56}$Ni does not have sufficient impetus to escape the black hole (Heger et al. 2003; Fryer et al. 2006) or in jet-induced explosions with narrow jets when the deposited energy is small (Nomoto et al. 2007; Tominaga et al. 2007). Progenitor stars with relatively low angular momentum could also produce GRBs without supernovae (MacFadyen 2003). These seem attractive explanations at least for GRB 060505. In the absence of a GRB explosion, the detection of such quiet-death massive stars, if they exist, is a challenge for current instrumentation (e.g., Kochanek et al. 2008).

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Fig. 3.—Lag-luminosity relation using data (diamonds) and fit from Norris et al. (2006a). In addition, GRB 060505 (open circle), GRB 060614 (filled square; Gehrels et al. 2006), short GRBs (open squares), and three GRBs associated with SNe (filled circles) are included. The lag values are from the following: GRB 060218, Liang et al. (2006); GRB 031203, Foley et al. (2008); GRB 980425, Norris (2002). The spectral lag of GRB 060505 is significantly longer than those measured for short GRBs, and it falls on the lag-luminosity plot in a position similar to that of some SN GRBs. The diamond and filled-circle lag values are determined between the 25–50 and 100–300 keV energy ranges. Lags for GRB 060614 and the short bursts are measured between the 15–25 and 50–100 keV ranges. No k-correction is applied.