LETTERS

# A new γ-ray burst classification scheme from GRB 060614

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**Gamma-ray bursts (GRBs) are known to come in two duration classes[1], separated at ∼2 s. Long-duration bursts originate from star-forming regions in galaxies[2], have accompanying supernovae when these are near enough to observe and are probably caused by massive-star collapsars[3]. Recent observations[4–10] show that short-duration bursts originate in regions within their host galaxies that have lower star-formation rates, consistent with binary neutron star or neutron star–black hole mergers[11,12]. Moreover, although their hosts are predominantly nearby galaxies, no supernovae have been so far associated with short-duration GRBs. Here we report that the bright, nearby GRB 060614 does not fit into either class. Its ∼102-s duration groups it with long-duration GRBs, while its temporal lag and peak luminosity fall entirely within the short-duration GRB subclass. Moreover, very deep optical observations exclude an accompanying supernova[13–15], similar to short-duration GRBs. This combination of a long-duration event without an accompanying supernova poses a challenge to both the collapsar and the merging-neutron-star interpretations and opens the door to a new GRB classification scheme that straddles both long- and short-duration bursts.**

The Burst Alert Telescope (BAT) onboard the Swift satellite[16] detected GRB 060614 on 14 June 2006 at 12:43:48 UT. Using the initial positions from the onboard X-ray and ultraviolet/optical telescopes, the burst was subsequently located by ground- and space-based telescopes at the outskirts of a relatively nearby faint dwarf galaxy at a redshift of $z = 0.125$ (ref. 17). We do not find the suggestion[18,19] of a chance alignment between a background GRB and foreground galaxy at $z = 0.125$ to be credible; the probability of the observed 0.5" offset between the GRB and the $z = 0.125$ galaxy occurring by chance is only $2 \times 10^{-5}$. Also, fits to the combined ultraviolet/optical and X-ray telescope spectra give $z < 1.3$ at the 99.99% confidence level, excluding the suggested[18] location at $z > 1.4$ (see ref. 14 for additional evidence against a chance alignment).

The event's duration, $T_{90} = 102$ s (15–350 keV; where $T_{90}$ is the time during which 90% of the event photons were collected), clearly places GRB 060614 in the long-duration burst category[1]. The event was also at close proximity, so it became a prime candidate for a supernova search in its light curve, as indeed had been found in four individual cases in the past[20]. The three accompanying papers[13–15] report very tight upper limits—100 times lower than previous detections—in these searches. Thus far, strict supernova limits had been found only for the GRBs of the short-duration variety. So why was there no supernova associated with the long-duration GRB 060614?

A close examination of the BAT light curve of GRB 060614 (Fig. 1) reveals a first short, hard-spectrum episode of emission (lasting 5 s) followed by an extended and somewhat softer episode (lasting ∼100 s). The total energy content of the second episode is five times that of the first, with fluences of $(1.69 \pm 0.02) \times 10^{-5}$ erg cm$^{-2}$ and $(3.3 \pm 0.1) \times 10^{-6}$ erg cm$^{-2}$, respectively, in the 15–350 keV band. The recent discovery of a similar two-component emission structure in several Swift and the High Energy Transient Explorer 2 (HETE-2) spacecraft short-duration GRBs prompted Norris and Bonnell[21] to search the Burst And Transient Source Experiment (BATSE) GRB database for similar events. They found three bursts with a bright softer emission component, spectrally similar to that of GRB 060614 (corresponding to roughly ∼1% of the number of short-duration BATSE GRBs). Weaker soft components are found in four of 16 Swift and HETE-2 short bursts and 11 out of 130 short-duration GRBs observed by the Konus spacecraft[22], which represents ∼10–25% of their short-duration GRB databases. It may be that the majority of short bursts have such soft components, since at present only two Swift short-duration GRBs (GRB 051221A and GRB 060313) are bright enough to allow low fractional limits to be set. We note that, regardless of their duration, almost all of these events with softer components have a common appearance: a 5–10-s gap between the first and second episodes and a hump-shaped second component.

Another method of distinguishing categories of GRBs is to compute the temporal lags between their light curve features in different energy bands[21,23,24]. We introduce a new variant on this approach by including short bursts in a plot of peak luminosity ($L_{peak}$) versus lag ($t_{lag}$); the redshift measurements from the past year for a number of short-duration Swift GRBs now makes the comparison possible. There is an anti-correlation between $t_{lag}$ and $L_{peak}$ for long bursts as shown in Fig. 2. In contrast, short bursts have small $t_{lag}$ and small $L_{peak}$ and occupy a separate area of parameter space from long bursts. The lag for GRB 060614 for the first 5 s is $3 \pm 6$ ms. Thus, in spite of its long duration, GRB 060614 falls into the same region of the lag–luminosity plot as do short bursts. Moreover, we were able to accurately calculate a lag for the softer second episode, owing to its spiky light curve. We find $t_{lag} = 3 \pm 9$ ms, consistent with the short, hard episode, and thus indicating a similar origin. The physical cause of lags in GRBs is not yet well understood, but it has been suggested[23] that bursts with smaller lags have more relativistic outflows.

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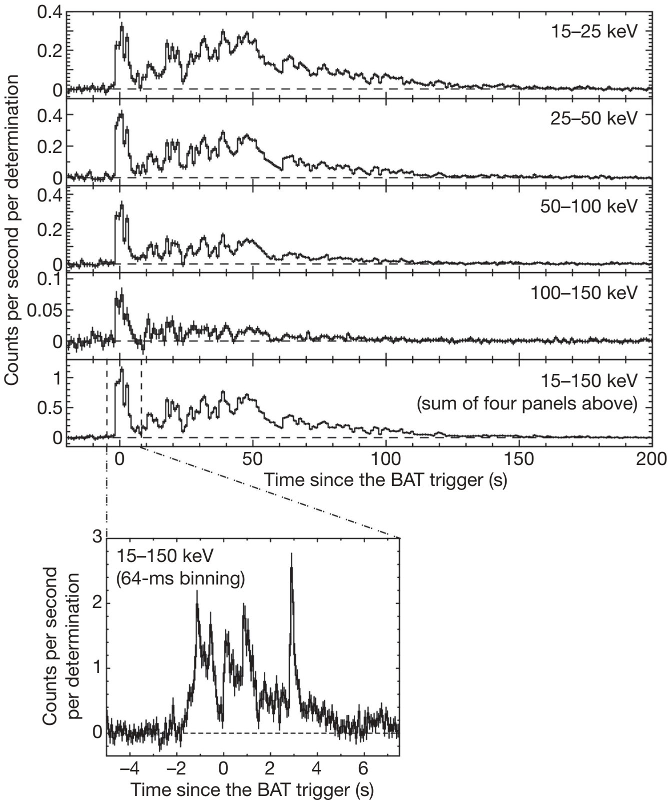


**Figure 1 | The light curve of GRB 060614 as observed with the BAT.** The mask-tagged BAT light curve is shown in four energy bands in the top panels, and these are summed in the bottom panel. The inset gives an expanded view of the first episode. There is a hint of a 9-s periodicity between 7 and 50 s, but it is not statistically significant. The spectrum is well fitted by a power law in both intervals with a photon index of $1.63 \pm 0.07$ in the first 5 s and a softer index of $2.02 \pm 0.04$ in the following 120 s. The burst was also detected with Konus-WIND[29] with $E_{peak} = 302$ $(-83, +214)$ keV in the first 5 s. The total energy radiated, assuming isotropic emission, $E_{iso}$, in the 1 keV–10 MeV range in the GRB restframe for the first 5 s is $1.8 \times 10^{50}$ erg. We note that the $E_{peak}$–$E_{iso}$ value for the short episode falls far away from the Amati relationship for long-duration bursts. The spacecraft repointed the X-ray and ultraviolet/optical telescopes at the burst in 90 s. The X-ray emission (0.3–10 keV) was initially among the brightest until now at $5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ at 100 s. The afterglow light curves suggest a jet break at ~1.5 days, implying a narrow jet occupying $\leq 10^{-2}$ of the total solid angle and suggesting an energy of $\sim 10^{49}$ erg in the relativistic jet, roughly comparable to that inferred for Swift short-duration GRBs.

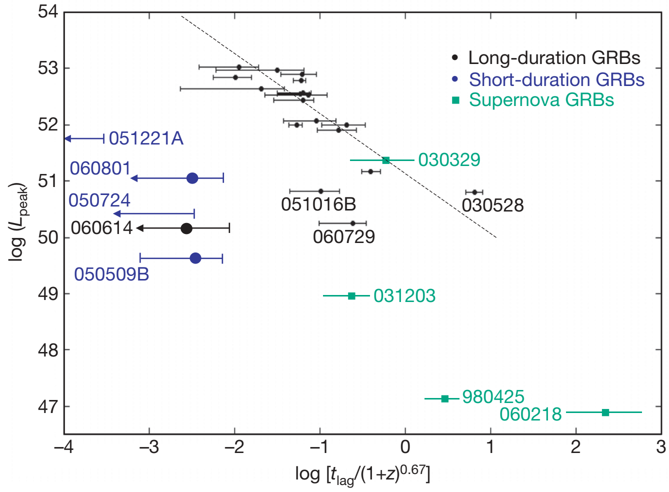


**Figure 2 | Spectral lag as a function of peak luminosity showing GRB 060614 in the region of short-duration GRBs.** The lags and peak luminosities are corrected to the source frame of the GRB. The lags are defined as the time difference between light curve structures in the 50–100 keV and 15–25 keV channels. The energy correction (K-correction) to the source frame for the lag is approximately $(1+z)^{0.33}$, making the total energy correction plus time dilation correction $(1+z)^{-0.67}$. The data points labelled as long bursts are from Swift/BAT, with the exception of GRB 030528 which is a very long-lagged HETE-2 burst. The dashed line illustrates the lag–luminosity correlation for long bursts. Outliers are bursts with unusual properties: GRB 060729 has an extremely long-lived afterglow and GRB 051016B has extremely soft prompt emission. The blue data points for short bursts are from Swift/BAT. The peak luminosity was calculated for the short bursts and GRB 060614 using 64-ms binning. In green are the four nearby long-duration GRBs with associated supernovae. Three of the four supernovae-associated underluminous nearby GRBs (GRB 980425, GRB 031203 and GRB 060218) fall below the long-burst correlation, while the only supernova-associated GRB with normal luminosity (GRB 030329) falls near the line, further suggesting that it is a normal GRB (the only normal burst with a firm supernova association). None of the supernova-associated GRBs falls near the short grouping. Note that our detailed calculation of the lag of GRB 030329 gives a larger value here than previously found[30] in a higher energy band. All error bars are 1$\sigma$.

It is thus difficult to determine unambiguously which category GRB060614 falls into. It is a long-duration event by the traditional definition, but it lacks an associated supernova as observed in other nearby long-duration GRBs, and it shows morphological similarities with Swift short bursts. Further, the complex structure of the second component and lag similar to the first component indicates that the extended episode is due to the long-lived activity of the burst's central engine rather than due to the onset of the afterglow emission. However, its spectral lag and low luminosity make it distinct from other long-duration GRBs and place it instead with short bursts. Perhaps the odd characteristics of GRB 060614 point to a new subclass with a different physical origin identified by a third GRB property, namely spectral lag. However, we first must ask what would be needed to fit such a class of events into either the collapsar or merger models.

Short, hard bursts with continuing activity resembling long, soft bursts are a prediction of some massive star models[25], favoured when the pre-explosive mass loss is unusually high and the jet energy low. The lack of a supernova requires that most production of $^{56}$Ni is avoided during the star collapse. This might be possible if the disk wind is weak and if $^{56}$Ni that had been produced initially fell back onto the collapsed core in a weak supernova explosion. Nevertheless, producing less than $10^{-3}$ solar masses of $^{56}$Ni is a challenge for the collapsar model[26]. Another possibility is a failed supernova; the small observed lag may imply a higher-velocity outflow with insufficient energy deposited in the star for it to explode. In the neutron-star merger model, the duration of GRB 060614 is a problem. The duration is set by the lifetime of the accretion disk around the newly born black hole and is expected[27] to be ~0.1 s. The accretion during a black hole–neutron star merger might be longer if, as suggested by simulations[28], a significant amount of mass is ejected to a bound orbit and falls back into the black hole on timescales larger than 1 s. We conclude that although GRB 060614 may be just another odd event in the motley-crew collection of GRBs, it is more probably one of the first-established members of an emerging class of events that includes both short- and long-duration GRBs.

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