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A novel explosive process is required for the γ-ray burst GRB 060614

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Over the past decade, our physical understanding of γ-ray bursts (GRBs) has progressed rapidly, thanks to the discovery and observation of their long-lived afterglow emission. Long-duration ($\gtrsim$2 s) GRBs are associated with the explosive deaths of massive stars ('collapsars', ref. 1), which produce accompanying supernovae[2–5]; the short-duration ($\lesssim$2 s) GRBs have a different origin, which has been argued to be the merger of two compact objects[6–9]. Here we report optical observations of GRB 060614 (duration ~100 s, ref. 10) that rule out the presence of an associated supernova. This would seem to require a new explosive process: either a massive collapsar that powers a GRB without any associated supernova, or a new type of 'engine', as long-lived as the collapsar but without a massive star. We also show that the properties of the host galaxy (redshift $z = 0.125$) distinguish it from other long-duration GRB hosts and suggest that an entirely new type of GRB progenitor may be required.

On 14 June 2006, at 12:43 UT, the burst alert telescope (BAT) on board the Swift satellite detected GRB 060614[10], with a duration of 102 s. Detailed information was collected by the Swift BAT, X-ray telescope (XRT) and ultraviolet-optical telescope[11] (UVOT). In particular, the burst showed strong variability during much of that period, as confirmed by parallel observations by the Konus-Wind satellite[12], indicating sustained energy injection from an active engine, rather than the early onset of the afterglow (radiation from the interaction of an expanding outflow). We began observing this event ~26 min later using the 40-inch telescope at Siding Springs Observatory (SSO). The evolution of the optical radiation from this event as traced by our data, augmented by Swift observations and additional data from the literature, is shown in Fig. 1 (see Supplementary Information for data tables). As the optical source decayed, we noticed that it was apparently superposed on a faint dwarf host galaxy. On 19 June 2006 UT we obtained a spectrum of the host using the GMOS-S spectrograph mounted on the Gemini South 8-m telescope at Cerro Pachon, Chile. From this spectrum we derived the redshift of the host galaxy, $z = 0.125$, which is a low value for long GRBs. We confirmed this redshift with a higher quality spectrum obtained using the same instrument on 15 July 2006 UT (Supplementary Information section 2). Previous long GRBs at such low redshifts showed clear signatures of the underlying supernova explosions at comparable age post-burst[3,13]. However, such signatures were lacking in the case of this long GRB[14].

Thus motivated, we undertook target-of-opportunity observations with the Hubble Space Telescope (HST). We observed the location of GRB 060614 using the Wide Field and Planetary Camera 2 (WFPC2) on board HST on 27–28 June 2006 UT, and again using the Advanced Camera for Surveys (ACS) on 15–16 July, 29 July and 8 September 2006 UT. Inspection of the data (Fig. 2) reveals a point source offset from the GRB host nucleus, which is well-detected in our first-epoch WFPC2 observations, and is apparently gone during our next visit. We identify this object as the optical afterglow of GRB 060614, and derive its brightness using image-subtraction methods. These high-resolution HST data strongly support the association of the GRB with the $z = 0.125$ host (Supplementary Information section 1). Our analysis (Fig. 1) shows that our HST detection is probably dominated by the afterglow (that is, residual decaying radiation from the interaction of the GRB ejecta with itself and/or the surrounding material), rather than a possible supernova (whose optical radiation is dominated by energy released from radioactive decay of newly synthesized elements, mostly ^{56}Ni), which is not required by the data. Any putative supernova component must be more than 100 times fainter than the faintest event previously known to be associated with a long GRB (supernova SN 2006aj/GRB 060218[13,15]; Fig. 1). In fact, such a supernova (absolute V-band magnitude $M_V > -12.3$ mag, assuming V-band extinction $A_V < 0.2$; ref. 16) would be fainter than any supernova ever observed[17]. A conservative upper limit on the amount of synthesized ^{56}Ni is $5 \times 10^{-4} M_\odot$ (assuming that supernova peak luminosity scales with Ni mass[18]), which is more than two orders of magnitude less than the typical amount synthesized by long GRB/supernovae. Our HST data thus indicate that this GRB was not associated with a radioactively-powered event similar to any known supernova.

Furthermore, our HST and ground-based data reveal that the properties of the host of GRB 060614 and its environment are unusual when compared to those of the large sample of previously observed long GRBs. In particular, the star formation rate that we measure from the spectrum of the host, $0.0084 M_\odot\ \mathrm{yr}^{-1}$, is very small, and even the specific star formation rate, correcting for the low luminosity of this dwarf galaxy ($M_B = -15.9$ mag) is about ten times

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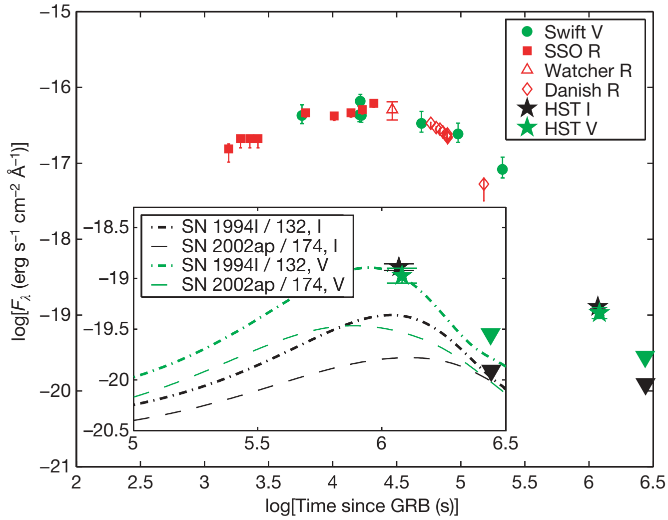

Figure 1 | Temporal evolution of the optical transient associated with GRB 060614. The main figure shows Swift V-band observations from UVOT (green filled circles), our SSO R-band data (red filled squares), augmented by R-band data from the Danish[14] and Watcher[21] groups (open red triangles and diamonds), along with our late time HST V- and I-band detections (green and black stars) and upper limits (green and black filled inverted triangles; see Fig. 2). The contribution of the host galaxy, estimated as detailed in Supplementary Information section 2, was removed from the photometry. Error bars (1σ) include root-mean-square photometric errors and calibration uncertainties added in quadrature, and are sometimes smaller than the symbols. The inset shows a comparison of our HST detections and upper limits with scaled-down light curves of supernovae, properly k-corrected and time-dilated[18]. The brightest allowed supernova is obtained by assuming the steeply declining light curve of SN 1994I, scaled down by a factor of 132 (heavy green (V) and black (I) dash-dot lines) and the maximal amount of extinction allowed by the analysis of early UVOT and XRT data[16]. In this case the absolute peak magnitude of the supernova will be $M_V = -12.3$, fainter than any supernova ever detected in the nearby Universe, synthesizing only $\sim 5 \times 10^{-4} M_\odot$ of ^{56}Ni (assuming that Ni mass scales with peak luminosity[18]). More likely scenarios involving supernovae with more slowly-decaying light curves—such as SN 2002ap[25,26], scaled down by a factor of 174 (thin green (V) and black (I) dashed lines), which is similar to the faintest GRB-associated supernova SN 2006aj—would impose more stringent limits on the luminosity and ^{56}Ni production of a putative supernova (by factors of $\sim$2). At least the I-band emission detected during our first HST visit must be dominated by the GRB afterglow emission, with but a fraction of the light coming from a peaking faint supernova. Note that the data are well-explained without invoking any supernova-like component, with the optical afterglow roughly following the late X-ray decline rate[11] (to which a supernova is not expected to contribute).

below that of typical long GRBs[19]. Moreover, the location of the GRB, well-separated from areas of the host which are brightest at rest-frame ultraviolet wavelengths, is atypical for a long GRB (only 1–2 bursts out of 32 (ref. 20) lie in locations that are fainter in the ultraviolet; see Supplementary Information section 2).

Considering the entire set of observations available for this event, the emerging picture is a puzzling one. On the one hand, the high-energy (γ-ray) duration of this burst is only consistent with that of a long GRB. On the other hand, the lack of an associated supernova is inconsistent with an origin in a massive, rapidly-rotating star undergoing a core-collapse supernova explosion (a collapsar[1])—the popular, observationally supported model for long GRBs. Furthermore, the environment and host galaxy properties of this event stand out from among those of numerous other long GRBs observed so far[19,20].

One may conjecture that all long GRBs result from massive collapsars, but that most of these are associated with supernovae with a range of properties (as observed so far[18,21]) and a minority (the first unambiguous example of which is GRB 060614[14]) synthesize very little ^{56}Ni, and do not produce an optically luminous supernova. If this is indeed the case, the putative massive progenitor star is probably different from those of long GRBs, given its remarkable environment and host.

Alternatively, in view of the host galaxy properties, one might suggest that this event may not be associated with a massive stellar

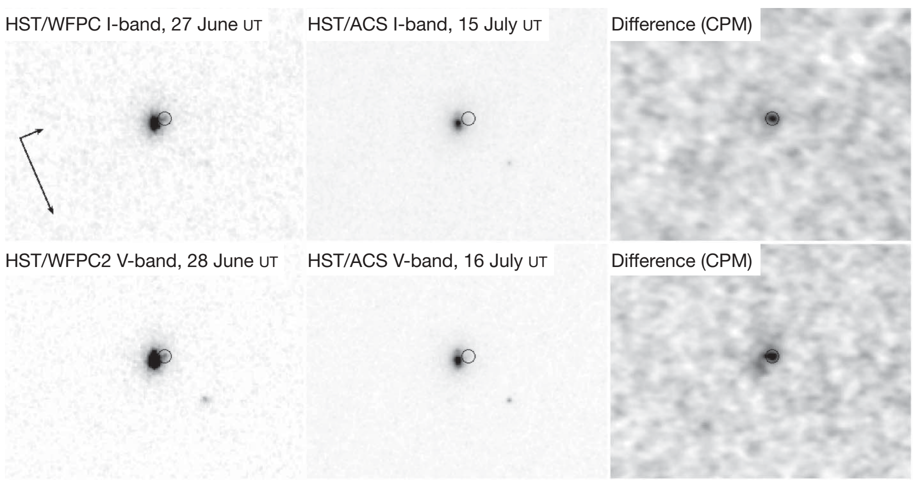

Figure 2 | HST observations of the location of GRB 060614. Top panels, I-band (F814W filter) data; bottom panels, V-band (F606W) data. Images were obtained using the WFPC2 camera (leftmost panels, 6,000 s total exposure time; UT dates as marked) and the ACS camera (middle panels, 3,600 s). Rightmost panels show the difference between the first epoch images and a third epoch visit with ACS (I-band; 29 July 2006 UT, total exposure time 4,840 s) or the second epoch in the case of the V-band, calculated using the image subtraction method CPM[27]. WFPC2 data were reduced using custom scripts[28] and ACS data were reduced and photometry carried out in the standard manner with IRAF/multidrizzle and then calibrated to standard bands[29]. We used calibrated, nearby, isolated, compact sources to establish a calibration grid of Johnson-V and Cousins-I local standards and photometered the afterglow with respect to this grid using the image-subtraction-based photometry pipeline mkdifflc[27]. A similar comparison between the second and third I-band (16 and 29 July UT) and V-band (15 July and 8 September) HST visits shows no residual to a 4σ upper limit of $I(V) = 27.5(27.75)$ mag, indicating that the optical transient was undetectable during our second visit. The resulting photometry and upper limits are reported in Fig. 1 and Supplementary Information section 3. Note the overall regular structure of this faint dwarf host and the peripheral location of the optical transient (see Supplementary Information section 2 for further details). The orientation of the images is marked with a long arrow due north and a short arrow due east. The length of the long arrow is 2.5″ for scale. The black circle in all panels indicates the location of the afterglow as derived from the subtraction frames (right panels).

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progenitor. Such a lower-mass long-lived progenitor system may be similar to those of short GRBs, which have been shown to reside in host galaxies of all types, including elliptical galaxies with virtually no young, massive stars[6,7,8], and in the outskirts of dwarf galaxies[22], indicating a mature (rather than short-lived) population of progenitors (lacking associated supernovae). If this is the case, we predict that eventually a long event like GRB 060614 will be discovered in an elliptical host. If GRB 060614 and short GRBs share a common physical origin, maintaining its proposed identification as a compact binary merger is a challenge to the current consensus view, according to which this process lasts for but a fraction of a second[23].

Finally, GRB 060614 may be the first example of a new class of GRBs, different from both typical long events (which are associated with supernovae and powered by infall onto a newly formed black hole) and short events (which may come from compact binary mergers). Regardless of the ultimate resolution of this puzzle, it is already obvious that the elegant simple picture—consisting of two groups of GRBs with distinct physical origins (long GRBs from supernova/collapsars and short GRBs from binary mergers), which was briefly consistent with GRB observations and theory—must now be revised.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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