A short $\gamma$-ray burst apparently associated with an elliptical galaxy at redshift $z = 0.225$

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Gamma-ray bursts (GRBs) come in two classes: long (2 s), soft-spectrum bursts and short, hard events. Most progress has been made on understanding the long GRBs, which are typically observed at high redshift ($z \approx 1$) and shown in subluminous star-forming host galaxies. They are likely to be produced in core-collapse explosions of massive stars. In contrast, no short GRB had been accurately (10$^{-1}$) and rapidly (minutes) located. Here we report the detection of the X-ray afterglow from—and the localization of—the short burst GRB 050509B. Its position on the sky is near a luminous, non-star-forming elliptical galaxy at a redshift of 0.225, which is the location one would expect if the origin of this GRB is through the merger of neutron-star or black-hole binaries. The X-ray afterglow was weak and faded below the detection limit within a few hours; no optical afterglow was detected to stringent limits, explaining the past difficulty in localizing short GRBs.

The new observations are from the Swift satellite, which features the hard X-ray wide-field Burst Alert Telescope (BAT), and rapid spacecraft slewing to point the narrow-field X-ray Telescope (XRT) and the Ultraviolet-optical Telescope (UVOT) at the burst. On 9 May 2005 at 04:00:19.23 UT, the BAT triggered and located GRB 050509B on board. The BAT location is shown in Fig. 1 (large red circle) and the light curves in Fig. 2. The event is a single short spike with duration of 40 ± 4 ms. The burst has a ratio of 50–100 keV to 25–25 keV fluences of 1.4 ± 0.5, which is consistent with, but in the soft portion of, the short/hard population detected by the first extensive GRB survey made with the Burst and Transient Source Experiment (BATSE). The 15–150 keV fluence is (9.5 ± 2.5) × 10$^{-9}$ erg cm$^{-2}$, which is the lowest imaged by BAT so far and is just below the short GRB fluence range detected by BATSE (adjusted for the different energy ranges of the two instruments).

Swift slewed promptly and XRT started acquiring data 62 s after the burst ($T+62$ s, where $T$ is the BAT trigger time). Ground-processed data revealed an uncatalogued X-ray source near the centre of the BAT error circle containing 11 photons (5.7σ significance due to near-zero background in image) in the first 1.460 s of integration time. The XRT position is shown with respect to the Digitized Sky Survey (DSS) field in Fig. 1. A Chandra target-of-opportunity observation of the XRT error circle was performed on 11 May at 4:00 UT for 50 ks, with no sources detected in the XRT error circle. The light curve combining BAT, XRT and Chandra data are shown in Fig. 3. The UVOT observed the field starting at $T+60$ s. No new optical/ultraviolet sources were found in the XRT error circle to V-band magnitude $>19.7$ for $t < 300$ min.

Swift has provided the first accurate localization of a short GRB. No optical afterglow was detected to stringent limits (R-band magnitude $>25$ at 25 h; ref. 7). When the XRT error circle is plotted on the R-band image we obtained with the Very Large Telescope (VLT), several faint objects are seen in the error circle, some of which are extended and could be high-redshift galaxies. It is possible the burst occurred in one of these. However, the centre of the XRT error circle lies only 9.8$'$ away from the centre of the large E1 elliptical galaxy.
The large red circle is the BAT position error circle, and the smaller blue circle is the XRT position error circle. The BAT position is 12 h 36 m 18 s, +28° 59′ 28″ (J2000) with a 2.3″ error radius (90% containment). The XRT, operating in its most sensitive ‘photon counting’ mode, derived a position of 12 h 36 m 13.58 s, +28° 59′ 01.3″ (J2000), with a positional accuracy of 9.3″ (90% containment radius; larger than the typical XRT 4″ accuracy, owing to weakness of burst). This position takes into account the low counting statistics, cluster emission in the field and astrometric corrections to the 2MASS coordinate system. Many of the extended objects are likely to be galaxies in the cluster NSC J123610+285901 (refs 12, 13). The inset shows a blow-up of the region of the XRT error circle from an R-band image obtained using FORS2 on the 8.2-m VLT-Antu telescope at the European Southern Observatory/Paranal on 11 May UT, 1.85 days after the burst. The extended source to the right (west) is the luminous elliptical galaxy 2MASX J12361286+285858026, which we suggest to be the likely host of the burst. Other objects in the error circle are not identified, but appear to be faint galaxies either associated with the same cluster as the elliptical galaxy or at higher redshift. The VLT image consists of fifteen 3-min frames taken under good conditions (~1″ seeing).

Galaxy 2MASX J12361286+2858580 (ref. 10) at a redshift of 0.225 (ref. 11), which is located in the cluster NSC J123610+285901 (refs 12, 13). This is a luminous giant elliptical galaxy; its 2 Micron All Sky Survey (2MASS) magnitude of K = 14.1 corresponds to a luminosity of $4 \times 10^{11} L_{\odot} \approx 3 L^*$, where $L_{\odot}$ is the luminosity of the Sun and $L^*$ is the luminosity of a typical galaxy, assuming standard cosmology. Our Chandra image shows that this is the central dominant galaxy in one of two merging subclusters in this bimodal cluster. Although caution is always prudent for a posteriori statistics, the association with this galaxy seems unlikely to be coincidental. The probability of a random location being within $10^\circ$ of a galaxy with an apparent magnitude at least this bright is $\sim 10^{-2}$. Moreover, galaxies this luminous are relatively rare; the comoving number density of galaxies at least this luminous is $\sim 5 \times 10^{-7}$ Mpc$^{-3}$; the probability of lying within $10^\circ$ of a randomly located one at $z \approx 0.225$ is $\sim 10^{-4}$. Note that this is the first GRB of $\sim 80$ with accurate optical localizations to be near a bright elliptical on the sky.

The likely association between GRB 050509B and 2MASX J12361286+2858580 is difficult to understand if the GRB resulted from any mechanism involving recent star formation. The galaxy type for the suggested host galaxy is very different from those found for long GRBs; their hosts are typically subluminous and blue and show strong emission lines associated with star formation. As is true of most giant ellipticals in clusters, 2MASX J12361286+2858580 has no indications of ultraviolet or optical line emission. Our UVOT images clearly detect the galaxy in the optical, but not in the ultraviolet (UVM2 220-nm and UVW2 188-nm filters), as expected for an elliptical galaxy—implying little or no contribution from young, hot stars. The 3σ upper limit at 188 nm gives a limit to the star-formation rate of $<0.2 M_{\odot}$ yr$^{-1}$, where $M_{\odot}$ is the mass of the Sun. It is improbable that we will find a massive-star core collapse or young magnetar in this galaxy. In addition, the isotropic energy of $1.1 \times 10^{58}$ erg (15–150 keV; $z = 0.225$, where the k-correction factor is typically 1 to 10) is $>10^{56}$ times higher than that of the 27 December 2004 giant flare from SGR 1806–20 (refs 18, 19), thus it is unlikely that this burst was an SGR-type flare.

On the other hand, 2MASX J12361286+2858580 is a very propitious site for a neutron star–neutron star or neutron star–black hole merger. As Chandra observations have shown, giant ellipticals, especially those dominant in their cluster, have large populations of low-mass X-ray binaries containing accreting neutron stars and black holes. Further, a high fraction ($\approx 50\%$) of the low-mass X-ray binaries in ellipticals are located in globular clusters because close binary systems containing at least one compact object can easily be formed dynamically in globular clusters. Although there is less direct evidence that close neutron star–neutron star binaries can form easily in globular clusters, the double-neutron-star system PSR B2127+11C in the Galactic globular cluster M15 is an example of such a binary, and has a merger lifetime of $\sim 2 \times 10^9$ yr. In fact, of
The X-ray emission for GRB 050509B is faint, being the weakest of any of the 15 GRBs that XRT has promptly observed (a factor of ~200 weaker than the XRT average). For BATSE bursts, studies were done of the post-burst emission by summing large numbers of GRB lightcurves and the post-burst emission was found to be weaker for short bursts than for long events, consistent with the GRB 050509B. For typical shock parameters, the early X-ray afterglow is probably below the cooling frequency; in this regime, the weak afterglow is consistent with the low-density medium around an evolved compact binary progenitor. A more critical factor to define the low X-ray flux may be the small energy injection involved, as the prompt emission for GRB 050509B is also the weakest of the BAT GRBs. If the redshift is 0.225, then the afterglow is >100 times less luminous than that of typical long-burst afterglows and the isotropic energy is ~10^{-4} that of typical long GRBs (about the same as the lowest-luminosity, unusual GRB 980425).

Before Swift’s observations, it was predicted that short GRBs would have faint optical afterglows, particularly so if they occurred in low-density regions like those around evolved stars. This prediction is consistent with the lack of optical detection to stringent limits for GRB 050509B, although we bear in mind that this burst is weak compared to other short GRBs. It is likely that the X-ray afterglow will remain a key to understanding short bursts.

The X-ray afterglow from this short GRB can constrain outflow parameters. The fact that the X-rays are fading as early as 62 s puts a limit on the initial Lorentz factor \( \Gamma_0 \) of 700 (at 1 kpc for a redshift of 0.225 and ambient density of 10^{-2} cm^{-3}) and \( E \) is the isotropic energy in units of 10^{51} erg, showing that short GRBs are highly relativistic events.

Another interesting aspect of the localization of GRB 050509B is that the burst is faint and yet has a bright galaxy in its error circle. There are five previous short GRBs with fluences one to three times of magnitude larger than GRB 050509B that have had their arcminute-sized error boxes searched for bright galaxies. There are galaxies in each error box of brightness comparable to or less than 2MASX 112361286+2858580, but none much brighter—as one might expect for these brighter GRBs. This does not contradict a merger model for short GRBs, because, although giant elliptical galaxies are a rich environment for mergers, most would occur in the more numerous, fainter, star-forming galaxies. Thus star-forming galaxies harbour both massive stars and evolved binaries, whereas ellipticals have almost no star formation and are highly deficient in short-lived massive stars. The detection of GRB 050509B near an elliptical galaxy is an important observation for short bursts because the association with a large elliptical galaxy is evidence against a collapsar origin, whereas an association with a star-forming galaxy would have left the question unanswered. There may be more than one origin of short GRBs, but this particular short event has a high probability of being unrelated to star formation and of being caused by a binary merger.
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