A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir1, A. J. Levan2, A. S. Fruchter3, J. Hjorth4, R. A. Hounsell3, K. Wiersema1 & R. L. Tunnicliffe2

Short-duration γ-ray bursts are intense flashes of cosmic γ-rays, lasting less than about two seconds, whose origin is unclear1–2. The favoured hypothesis is that they are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). This is supported by indirect evidence such as the properties of their host galaxies3, but unambiguous confirmation of the model is still lacking. Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species4,5, whose decay should result in a faint transient, known as a ‘kilonova’, in the days following the burst6–8. Indeed, it is speculated that this mechanism may be the predominant source of stable r-process elements in the Universe9,10. Recent calculations suggest that much of the kilonova energy should make an origin in massive stars unlikely (in contrast to long-duration γ-ray bursts, which result from the core collapse of some short-lived massive stars11). Progress in studying SGRBs has been slow; NASA’s Swift satellite localizes only a handful per year, and they are typically faint, with no optical afterglow or unambiguous host galaxy found in some cases despite rapid searches with large (8-m class) telescopes.

GRB 130603B was detected by Swift’s Burst Alert Telescope on 2013 June 3 at 15:49:14 UT17, and its duration was measured to be \( T_{90} \approx 0.18 \pm 0.02 \) s in the 15–350-keV band18. The burst was also detected independently by the Konus instrument on NASA’s Wind spacecraft, which found a somewhat shorter duration, \( T_{90} \approx 0.09 \) s in the 18–1,160-keV band19. This places the burst unambiguously in the short-duration class, which is also supported by the absence of the bright supernova emission generally found to accompany low-redshift \( z \lesssim 0.5 \), long-duration bursts (see below). The optical afterglow was discovered at the William Herschel Telescope20 and found to overlie a galaxy previously detected in the Sloan Digital Sky Survey imaging of its host.

Figure 1 | HST imaging of the location of GRB 130603B. The host is well resolved and has a disturbed, late-type morphology. The position (coordinates RA2000 = 11 h 28 min 48.16 s, Dec2000 = +17° 04′ 18.2″) at which the SGRB occurred (determined from ground-based imaging) is marked as a red circle (right-hand panels), lying slightly off a tidally distorted spiral arm. The left-hand panel shows the host and surrounding field from the higher-resolution optical image. The right-hand panels show, from left to right, the epoch-1 and epoch-2 imaging and their difference (epoch 1 minus epoch 2; upper row, F606W/optical; lower row, F160W/NIR). The difference images have been smoothed with a Gaussian of width similar to the point-spread function, to enhance any point-source emission. Although the resolution of the NIR image is inferior to that of the optical image, we clearly detect a transient point source that is absent in the optical.

1Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK. 2Department of Physics, University of Warwick, Coventry CV4 7AL, UK. 3Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218, USA. 4Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej, 30, 2100 Copenhagen, Denmark.

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this field. The redshifts of the afterglow21 and the host galaxy22 were both found to be $z = 0.356$.

Another proposed signature of the merger of two neutron stars or a neutron star and a black hole is the production of a kilonova (sometimes also termed a ‘macronova’ or an ‘r-process supernova’) due to the decay of radioactive species produced and initially ejected during the merger process—in other words, an event similar to a faint, short-lived supernova23–8. Detailed calculations suggest that the spectra of such kilonova sources will be determined by the heavy r-process ions created in the neutron-rich material. Although these models10–13 are still far from being fully realistic, a robust conclusion is that the optical flux will be greatly diminished by line blanketing in the rapidly expanding ejecta, with the radiation emerging instead in the near-infrared (NIR) and being produced over a longer timescale than would otherwise be the case. This makes previous limits on early optical kilonova emission unsurprising23. Specifically, the NIR light curves are expected to have a broad peak, rising after a few days and lasting a week or more in the rest frame. The relatively modest redshift and intensive study of GRB 130603B made it a prime candidate for searching for such a kilonova.

We imaged the location of the burst with the NASA/ESA Hubble Space Telescope (HST) at two epochs, the first $\sim 9$ d after the burst (epoch 1) and the second $\sim 30$ d after the burst (epoch 2). On each occasion, a single orbit integration was obtained in both the optical F606W filter (0.6 µm) and the NIR F160W filter (1.6 µm) (full details of the imaging and photometric analysis discussed here are given in Supplementary Information). The HST images are shown in Fig. 1; the key result is seen in the difference frames (right-hand panels), which provide clear evidence for a compact transient source in the NIR in epoch 1 (we note that this source was also identified24 as a candidate kilonova in independent analysis of our data on epoch 1) that seems to have disappeared by epoch 2 and is absent to the depth of the data in the optical.

At the position of the SGRB in the difference images, our photometric analysis gives a magnitude limit in the F606W filter of $R_{606,AB} > 28.25$ mag (2$\sigma$ upper limit) and a magnitude in the F160W filter of $H_{160,AB} = 25.73 \pm 0.20$ mag. In both cases, we fitted a model point-spread function and estimated the errors from the variance of the flux at a large number of locations chosen to have a similar background to that at the position of the SGRB. We note that some transient emission may remain in the second NIR epoch; experimenting with adding synthetic stars to the image leads us to conclude that any such late-time emission is likely to be less than $\sim 25\%$ of the level in epoch 1 if it is not to appear visually as a faint point source in epoch 2, however, that would still allow the NIR magnitude in epoch 1 to be up to $\sim 0.3$ mag brighter.

To assess the significance of this result, it is important to establish whether any emission seen in the first HST epoch could have a contribution from the SGRB afterglow. A compilation of optical and NIR photometry, gathered by a variety of ground-based telescopes in the few days following the burst, is plotted in Fig. 2 along with our HST results. Although initially bright, the optical afterglow light curve declines steeply after about $\sim 10$ h, requiring a late-time power-law decay rate of $\alpha \approx 2.7$ (where $F \propto t^{-\alpha}$ describes the flux). The NIR flux, on the other hand, is significantly in excess of the same extrapolated power law. This point is made most forcibly by considering the colour evolution of the transient, defined as the difference between the magnitudes in each filter, which evolves from $R_{606} - H_{160} \approx 1.7 \pm 0.15$ mag at about 14 h to greater than $R_{606} - H_{160} \approx 2.5$ mag at about 9 d. It would be very unusual, and in conflict with predictions of the standard external-shock theory25, for such a large colour change to be a consequence of late-time afterglow behaviour. The most natural explanation is therefore that the HST transient source is largely due to kilonova emission, and the brightness is in fact well within the range of recent models plotted in Fig. 2, thus supporting the proposition that kilonovae are likely to be important sites of r-process element production. We note that this phenomenon is strikingly reminiscent, in a qualitative sense, of the humps in the optical light curves of long-duration $\gamma$-ray bursts produced by underlying type Ic supernovae, although here the luminosity is considerably fainter and the emission is redder. The ubiquity and range of properties of the late-time red transient emission in SGRBs will undoubtedly be tested by future observations.

The next generation of gravitational-wave detectors (Advanced LIGO and Advanced VIRGO) is expected ultimately to reach sensitivity levels allowing them to detect neutron-star/neutron-star and neutron-star/black-hole inspirals out to distances of a few hundred megaparsecs26 ($z \approx 0.05–0.1$). However, no SGRB has been definitively found at any redshift less than $z = 0.12$ over the 8.5 yr of the Swift mission to date27. This suggests either that the rate of compact binary mergers is low, implying a correspondingly low expected rate of gravitational-wave transient detections, or that most such mergers are not observed as bright SGRBs. The latter case could be understood if the beaming of SGRBs was rather narrow, for example, and the intrinsic event rate was, as a result, two or three orders of magnitude higher than that observed by Swift. Although the evidence constraining SGRB jet opening angles is limited at present28 (indeed, the light-curve break seen in GRB 130603B may be further evidence for such beaming), it is clear that an alternative electromagnetic signature, particularly if approximately isotropic,
such as kilonova emission, could be highly important in searching for gravitational-wave transient counterparts.

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