A kilonova associated with short-duration gamma-ray burst 130603B.

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Short-duration gamma-ray bursts (SGRBs) are intense flashes of cosmic gamma-rays, lasting less than ~ 2 s, whose origin is one of the great unsolved questions of astrophysics today[1,2]. While the favoured hypothesis for their production is in relativistic jets created by the merger of two compact stellar objects (specifically, two neutron stars, NS-NS, or a neutron star and a black hole, NS-BH), supported by evidence such as the range of host galaxy properties[3], unambiguous confirmation of the model is still lacking. Mergers of this kind are expected also to create significant quantities of neutron-rich radioactive species, whose decay should result in a faint transient in the days following the burst, a so-called "kilonova"[4]. Indeed, it is speculated that this mechanism may be the predominant source of stable r-process elements in the Universe[4,5]. Recent calculations suggest much of the kilonova energy should appear in

the near-infrared (nIR) due to the high opacity created by these heavy r-process elements[6–9]. Here we report strong evidence for such and event accompanying SGRB 130603B. If this simplest interpretation of the data is correct, it provides (i) support for the compact object merger hypothesis of SGRBs, (ii) confirmation that such mergers are likely sites of significant r-process production and (iii) quite possibly an alternative, un-beamed electromagnetic signature of the most promising sources for direct detection of gravitational waves.

SGRBs have long been recognised as a distinct sub-population of GRBs[10], commonly argued to be most likely produced by NS-NS/NS-BH mergers[1,2]. If correct, this would mean that SGRBs may provide a bright electromagnetic (EM) signature of the most promising events for gravitational wave (GW) detection with the next generation of GW detectors[11]. Localising EM counterparts is an essential prerequisite to obtaining direct redshift measurements, and to further constraining the astrophysics of the sources.

However, the evidence supporting this progenitor hypothesis is essentially circumstantial: principally that many SGRBs seem to reside in host galaxies, or regions within their hosts, lacking ongoing star formation, thus making a massive star origin unlikely (cf. long-duration bursts, which arise in the core-collapse of some short-lived massive stars[12]). Unfortunately, progress in studying SGRBs has been slow; *Swift* only localises a handful per year, and they are typically faint, with no optical afterglow or unambiguous host galaxy found in some cases despite rapid and deep searches.

GRB 130603B was detected by the *Swift*/Burst-alert-telescope (BAT) at 2013-06-03 15:49:14 UT[13], which measured its duration to be $T_{90} \approx 0.18 \pm 0.02\,\mathrm{s}$ in the 15–350 keV band[14]. The burst was also detected independently by Konus-Wind which found a somewhat shorter duration, $T_{90} \approx 0.09$ s in the 18–1160 keV band[15]. This places the burst unambiguously in the short-duration class, which is also supported by the absence of bright supernova emission such as is generally found to accompany nearby long-duration bursts (see below). The optical afterglow was detected at the William Herschel Telescope (WHT)[16], and found to overlie a galaxy previously detected in the Sloan Digital Sky Survey (SDSS) imaging of this field. The redshift of both afterglow[17] and host galaxy[18] were found to be $z = 0.356$.

Another proposed signature of a NS-NS/NS-BH binary merger is the production of a so-called "kilonova" (sometimes also termed a "macronova" or "mini-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 supernova[4,19,20]. 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 models[6–9] are still far from being fully realistic, a robust conclusion is that the optical flux will be greatly diminished by line-blanketing in the differentially expanding ejecta, with the radiation emerging instead in the nIR, and stretched out over a longer time scale than would otherwise be the case. This makes previous limits on early optical kilonova emission unsurprising[21]. Specifically, the nIR light curves are expected to exhibit 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 of the location of the burst with the *Hubble Space Telescope* (*HST*) at two epochs, the first $\approx$ 9 days post-burst, and the second at $\approx$ 30 days. On each occasion, a single orbit integration was obtained in each of 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 the SI). The *HST* images are shown in Figure 1; the key result is seen in the difference frames (right hand panels) that provide clear evidence for a compact transient source in the nIR in epoch 1 (we note that this source was also identified as a candidate kilonova in independent analysis of our epoch 1 data[22]), which has apparently disappeared by epoch 2 and is absent to the depth of the data in the optical.

At the position of the GRB in the difference images, our photometric analysis gives $R_{606,\mathrm{AB}}$ >28.25 (2σ upper limit) and $H_{160,\mathrm{AB}} = 25.73 \pm 0.20$. In both cases, we fitted a model point-spread function (psf) and estimated the errors from the variance of the flux at a large number of locations chosen to have similar background to that at the position of the OT. We note that it may be there was still some transient emission 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 the first epoch in order for it not to appear visually as a faint point source in the second epoch, however, that would still allow the nIR magnitude in epoch 1 to be up to ~ 0.3 mag brighter.

In order 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 Figure 2, along with our *HST* results. Although initially bright, the optical afterglow light curve shows a steep decline after about $\approx$10 hr, requiring a post-break power-law decay rate of $\alpha = 2.7$ (where flux, $F \propto t^{-\alpha}$). 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 which evolves from $R_{606} - H_{160} \approx 1.7 \pm 0.15$ at about 14 hr to $R_{606} - H_{160} \gtrsim 2.5$ at about 9 days. It would be very unusual, and in conflict with predictions of the standard external-shock theory[23], 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 in fact the brightness is well within the range of recent models over-plotted in Figure 2, thus supporting the proposition that they are likely to be important sites of r-process element production. We note, this phenomenon is strikingly reminiscent, in a qualitative sense, of the red humps in the light curves of long-duration GRBs produced by the SNe type Ib/c which accompany them, albeit that here the luminosities are considerably fainter, and the emission redder. The ubiquity and range of properties of the late-time red transient emission in SGRBs will doubtless be tested by future observations.

The next generation of gravitational wave detectors (Advanced-LIGO and Advanced-VIRGO) are expected to ultimately reach sensitivity levels allowing them to detect NS-NS and NS-BH inspirals out to distances of a few hundred Mpc ($z \approx 0.05 - 0.1$)[24]. However, no short-duration GRB has yet been definitely found at any redshift less than $z = 0.12$ over the 8.5 yr of the *Swift* mission to date[25]. This suggests that either the rate of compact binary mergers is worryingly low for GW detection, or that most are not observed as bright SGRBs. The latter case could be understood if the beaming of SGRBs was rather narrow, for example, and hence the intrinsic event rate two or three orders of magnitude higher than that observed by *Swift*. Although the evidence constraining SGRB jet opening angles is limited at present[27] (indeed, the light curve break seen in GRB 130603B may be further evidence for SGRB beaming), it is clear that an alternative electromagnetic signature, particularly if approximately isotropic, such as kilonova emission, could be highly important in searching for GW transient counterparts.

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

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Author Contributions NRT wrote the *HST* proposal, performed the final photometric analysis of the *HST* data and took primary responsibility for writing the text of the paper. AJL contributed to all aspects of the observations and planning, particularly collating photometry and creating figure 2. ASF and RAH contributed to detailed planning of the observations, and took primary responsibility for initial processing of the *HST* imaging. JH, KW and RLT contributed to planning the observing and analysis strategies. All authors contributed to refining the text of the paper.

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Figure 1: *HST* imaging of the location of GRB 130603B (coordinates RA(J2000)= 11 28 48.16, DEC(J2000)= +17 04 18.2). The host is well resolved and displays a disturbed, late-type morphology. The location at which the GRB occurred (determined from ground-based imaging) is marked as a red circle, 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 next panels show in sequence the first epoch and second epoch imaging, and difference (upper row F606W/optical and lower row F160W/nIR). The difference images have been smoothed with a Gaussian of width similar to the psf, to enhance any point-source emission. Although the resolution of the nIR image is worse, we clearly detect a transient point source, which is absent in the optical.

Figure 2: the optical, nIR (lefthand axis) and X-ray (right hand axis) light curves. All upper limits are 2σ. The optical data (gri bands) have been interpolated to the F606W band and the nIR data to the F160W band using an average spectral energy distribution at ≈ 0.6 days (SED; see SI). *HST* epoch 1 points are bold symbols. The optical afterglow decays steeply after the first ≈ 0.3 days, and is modelled here as a smoothly broken power-law (dashed blue line). We note that the complete absence of late-time optical emission also places a limit on any separate ^{56}Ni driven decay component. The 0.3–10 keV X-ray data[26] are also consistent with breaking to a similarly steep decay (the dashed black line shows the optical light curve simply rescaled to match the X-ray points in this time frame), although the source dropped below *Swift* sensitivity by $\sim$48 hr post-burst. The key conclusion from this plot is that the source seen in the nIR requires an additional component above the extrapolation of the nIR afterglow (red dashed line) assuming that it also decays at the same rate. This excess infra-red flux corresponds to a source with absolute magnitude $M(J)_{\rm AB} \approx -15.35$ at $\sim$ 7 days post-burst in the rest frame. This is consistent with the favoured range of KN behaviour from recent calculations (despite their known significant uncertainties)[7–9], as illustrated by the model[7] lines (orange curves correspond to ejected masses of $10^{-2}\ M_{\odot}$–lower and $10^{-1}\ M_{\odot}$–upper respectively). The cyan curve shows that even the brightest predictions for optical r-process KN emission are negligible), which are added to the afterglow decay curves to produce predictions for the total nIR emission (solid red) curves.

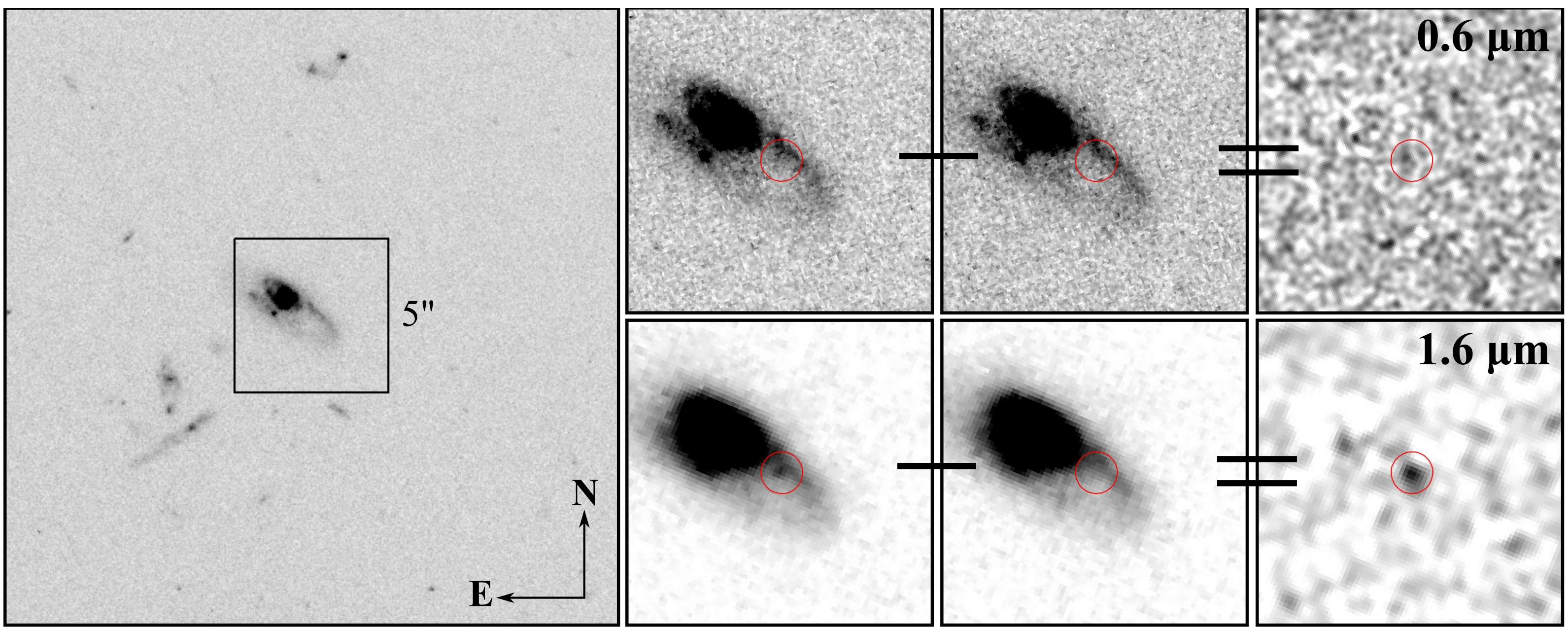
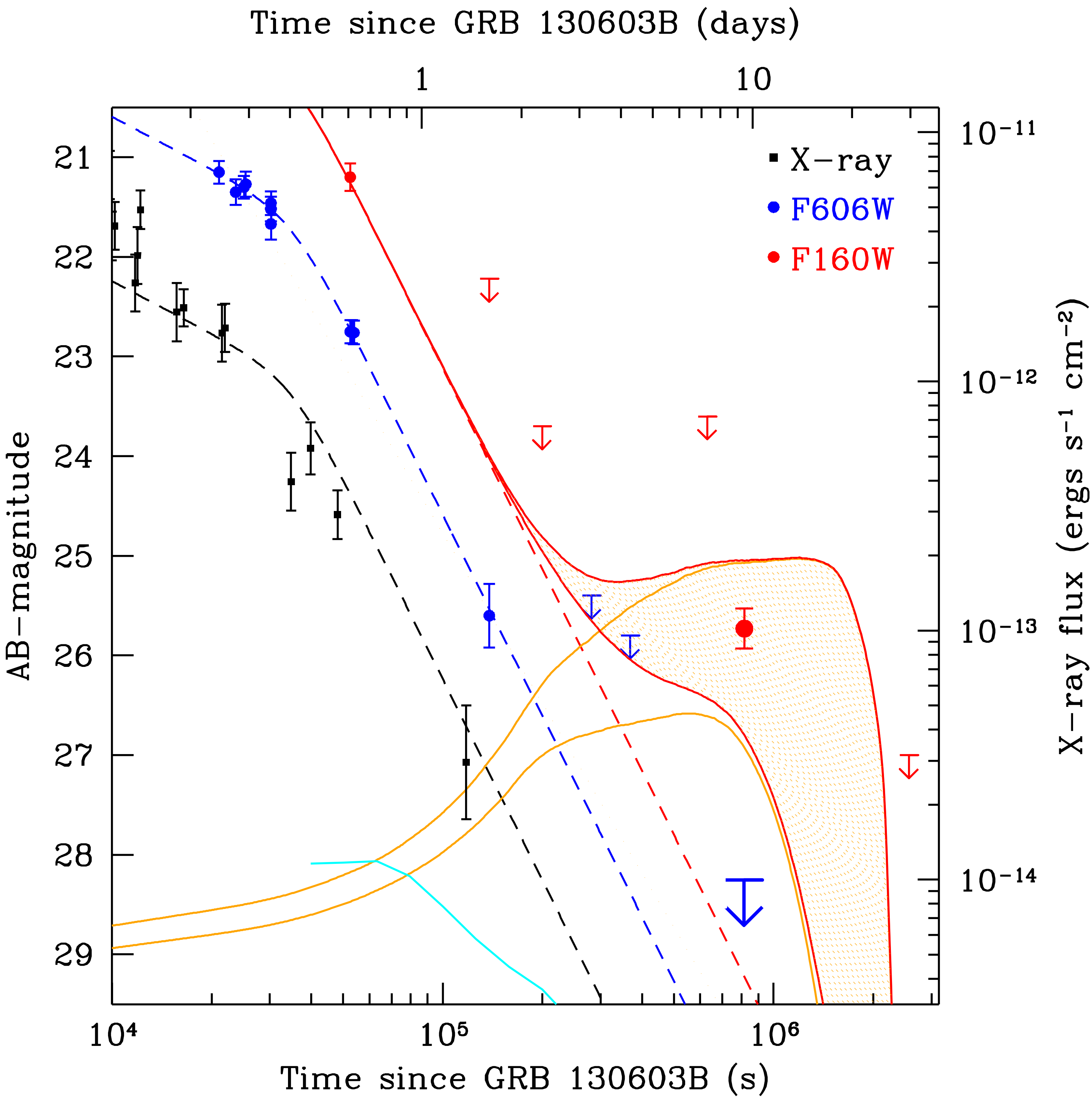


Figure 1



Time since GRB 130603B (days)
1
10
X−ray
F606W
F160W
AB−magnitude
21
22
23
24
25
26
27
28
29
X−ray flux (ergs s⁻¹ cm⁻²)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^4
10^5
10^6
Time since GRB 130603B (s)

Figure 2