Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger

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The merger of two neutron stars has been predicted to produce an optical–infrared transient (lasting a few days) known as a ‘kilonova’, powered by the radioactive decay of neutron-rich species synthesized in the merger1–5. Evidence that short γ-ray bursts also arise from neutron-star mergers has been accumulating6–8. In models2,9 of such mergers, a small amount of mass (10−4–10−2 solar masses) with a low electron fraction is ejected at high velocities (0.1–0.3 times light speed) or carried out by winds from an accretion disk formed around the newly merged object10,11. This mass is expected to undergo rapid neutron capture (r-process) nucleosynthesis, leading to the formation of radioactive elements that release energy as they decay, powering an electromagnetic transient1–3,9–14. A large uncertainty in the composition of the newly synthesized material leads to various expected colours, durations and luminosities for such transients11–14. Observational evidence for kilonovae has so far been inconclusive because it was based on cases15–19 of moderate excess emission detected in the afterglows of γ-ray bursts. Here we report optical to near-infrared observations of a transient coincident with the detection of the gravitational-wave signature of a binary neutron-star merger and with a low-luminosity short-duration γ-ray burst20. Our observations, taken roughly every eight hours over a few days following the gravitational-wave trigger, reveal an initial blue excess, with fast optical fading and reddening. Using numerical models21, we conclude that our data are broadly consistent with a light curve powered by a few hundredths of a solar mass of low-opacity material corresponding to lanthanide-poor (a fraction of 10−4.5 by mass) ejecta.

GW170817 was detected22 by the LIGO23 and Virgo24 gravitational-wave detectors on 17 August 2017 at 12:41:04 (universal time (UT) is used throughout; we adopt this as the time of the merger). Approximately two seconds later, a low-luminosity short-duration γ-ray burst, GRB 170817A, was detected25 by the Gamma-ray Burst Monitor (GBM) on board the Fermi satellite. A few hours later, the gravitational-wave signal was robustly identified as the signature of a binary neutron-star merger 40 ± 8 Mpc away in a region of the sky coincident with the Fermi localization of the γ-ray burst26 (Fig. 1).

Shortly after receiving the gravitational-wave localization, we activated our pre-approved program to search for an optical counterpart with the Las Cumbres Observatory (LCO) global network of robotic telescopes27. Given the size of the LIGO–Virgo localization region (about 30 square degrees) compared to the field of view of our cameras (about 0.2 square degrees), our search strategy involved targeting specific galaxies28 (chosen from the GLADE catalogue; http://aquarius.elte.hu/glade/) at the reported distance range...
of the Anglo-Australian Observatory Second Epoch Survey (AAO-SES),
archival image (left) taken on 9 April 1992 with the RG610 filter as part of the
Anglo-Australian Observatory Second Epoch Survey (AAO-SES), retrieved
via the Digitized Sky Survey (DSS).

and location area included in the LIGO–Virgo three-dimensional
localization (see Methods).

The fifth galaxy on our prioritized list was NGC 4993, an S0
galaxy 39.5 Mpc away. We observed the galaxy with the LCO 1-m
 telescopes at the Cerro Tololo Inter-American Observatory in Chile on
18 August 2017 at 00:15:23 and detected a new source at right ascension
\( \alpha_{2000} = 13 \text{ h} 09 \text{ m} 48.07 \text{ s} \) and declination \( \delta_{2000} = -23^\circ 22' 53.7'' \),
not present in archival images of that galaxy (Fig. 2; see Methods for
a timeline of the merger and ensuing immediate follow-up). We are
one of a few groups who discovered the same source within 45 min of
each other (see Methods). It was first announced by the Swope team,
who named it ‘SSS17a’, but here we use the official IAU designation,
AT 2017gfo.

Following the detection of this source, we initiated an intensive
follow-up campaign with LCO, obtaining multi-band images of
AT 2017gfo for several days, taken from each of our three Southern
Hemisphere sites (the Siding Spring Observatory in Australia, the
South African Astronomical Observatory, and the Cerro Tololo Inter-
American Observatory in Chile). AT 2017gfo was visible for less than
two hours each night owing to the proximity of its position on the sky to
the Sun, but having a multi-site observatory allowed us to obtain three
epochs of observations per 24-h period, capturing the rapid evolution
of the event (Fig. 3).

Our densely sampled light curve reveals that the optical transient
peaked approximately 1 day after the merger, followed by rapid fading
at a rate of about 2 mag per day in the g band, about 1 mag per day in the
r band, and about 0.8 mag per day in the i band. The rapid luminosity
decline is unlike that of any supernova (Extended Data Fig. 4),
but is broadly consistent with theoretical predictions of kilonovae (see,
for example, refs 2 and 3). From the temporal and spatial coincidence
of this event with both a gravitational-wave signal from a binary
neutron-star merger and a short-duration \( \gamma \)-ray burst, we conclude that
AT 2017gfo is the kilonova associated with the same merger.

We first compare our observations to analytical models from the
literature. The short rise time and luminous bolometric peak of more
than \( 3 \times 10^{44} \text{ ergs}^{-1} \) (as indicated by blackbody fits to post-shock multi-
colour data; see Methods) are consistent with a low-opacity ejected
mass according to available analytical models\(^{11,32}\), but the observed
high early temperature is not (see Methods).

With this in mind, we compare the observations to detailed
numerical radiation transport models of kilonova light curves and
spectra\(^{11}\). The model parameters are the total ejecta mass, the
characteristic expansion velocity, defined as \((2E/M_{\odot})^{1/2}\) (where \(E\) is the total
kinetic energy imparted on the ejecta mass \(M_{\odot}\)), and the mass fraction
of lanthanide species, which are crucial in setting the opacity.
This model solves the multi-wavelength radiation transport equation
using detailed opacities derived from millions of atomic lines, while
self-consistently calculating the temperature and ionization/excitation
state of the radioactively heated ejecta (see ref. 21 for more details).
This allows us to match the per-band light curves, rather than the
bolometric luminosity.

This approach produced a better match to our data, reproducing
most of the luminosity evolution (except in the g band; see below) using
an ejecta mass of \((2–2.5) \times 10^{-2} M_{\odot}\) (where \(M_{\odot}\) is the solar mass), a
characteristic ejecta velocity of 0.3c (where \(c\) is the speed of light) and a
low lanthanide mass fraction of \(X_{\text{lan}} = 10^{-4.5}\) (Fig. 3), corresponding to
an effective opacity of \(\kappa \lesssim 1 \text{ cm}^2 \text{ g}^{-1}\) (similar parameters also fit our
optical spectra presented in ref. 33). This is evidence that the merger
produced a component of ejecta composed primarily of light (atomic
number \(A \lesssim 140\)) r-process isotopes. In contrast, the lanthanide mass
fraction expected from the production of heavy r-process elements is
\(X_{\text{lan}} = 10^{-2} \text{–}10^{-1}\) (ref. 34), corresponding to \(\kappa \approx 10 \text{ cm}^2 \text{ g}^{-1}\). A substan-
tial mass of ejecta must therefore have experienced substantial weak
interactions, owing to shock heating or neutrino interactions; these
interactions would have raised the proton-to-neutron ratio from its
initial value in the neutron star. In such a case, the neutrons available
for capture would be exhausted before nucleosynthesis could build up
a noticeable abundance of elements with \(A \gtrsim 140\).

The discrepancy in the g band (and a smaller discrepancy in the
r band) may be due to a composition gradient in the ejecta (the model
we used assumes a uniform composition). A radial gradient in the
lanthanide abundance, in which \(X_{\text{lan}}\) varies from about \(10^{-8}\) in the
outermost layers to about \(10^{-4}\) in the interior layers, could lead to faster
reddening of the emission\(^{11}\), which may fit the data better. Even more
lanthanide-rich ejecta \((X_{\text{lan}} > 10^{-4})\) could be revealed through emission at
later times and redder wavelengths than covered by our data\(^{12-14}\).

Luminous infrared emission \((J \approx 17 \text{ mag}, H \approx 16 \text{ mag}, K_s \approx 15.5 \text{ mag};
although some of this emission may be contributed by the host galaxy)\)
is indeed found in observations taken 2.5 days and 3.5 days after the
merger\(^{15}\). It is possible that an additional source of radiation, perhaps
related to the \(\gamma\)-ray burst engine, contributes to the early blue emission,
and could provide an alternative explanation for the g- and r-band discrepancies. Future modelling efforts will need to explore these options and their effects on the predicted light curves.

The discovery of a kilonova coincident with gravitational waves from a binary neutron-star merger and with a short burst of γ-rays provides striking evidence in favour of the main theoretical picture of neutron-star mergers. These detections confirm that binary neutron-star mergers produce kilonovae with emission properties broadly in agreement with theoretical predictions. Our early optical to near-infrared light curve shows evidence for a lanthanide-poor component of the mass ejected in the merger, and indications for a blue power source in addition to radioactive decay. The rapid optical evolution explains why transient surveys have so far not detected such events, but the upcoming Large Synoptic Survey Telescope will detect the optical emission of hundreds of kilonovae per year out to distances beyond those accessible to current gravitational-wave detectors (see Methods).

Online Content Methods, along with any additional Extended Data display items and these sections appear only in the online paper.

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METHODS

Gravitational wave follow-up strategy and kilonova discovery. The Las Cumbres Observatory (LCO)27 consists of 20 telescopes (two 2-m, nine 1-m and nine 0.4-m in diameter) at six sites around the world, operated robotically as one network using dynamical scheduling software. As stated in the main text, we use a galaxy-targeted follow-up strategy rather than a tiling one25. Our galaxy selection strategy prioritizes galaxies that are at higher-probability locations and distances in the gravitational-wave localization region25; that have a higher intrinsic B-band luminosity (indicative of higher mass), and in which LCO is more likely to be sensitive to a kilonova. More details are provided in ref. 36. The timeline of the discovery, immediate follow-up and the visibility of NGC 4993 are depicted in Extended Data Fig. 1. In addition to our detection, AT 2017gfo was independently detected by the Swope, DECam, DLT40, MASTER and VISTA groups31,43,44,45.

Photometry. Images from the LCO 1-m telescopes were pre-processed using the Python-based BANZAI pipeline. Photometry was then extracted using the PyRAF-based LCOGTstamp pipeline45 by performing image subtraction45 followed by point spread function fitting. We use images taken after the kilonova faded below our detection limits as subtraction references. Our point spread function fitting. We use images taken after the kilonova faded below our detection limits as subtraction references. Our point spread function fitting. We use images taken after the kilonova faded below our detection limits as subtraction references. Our point spread function fitting. We use images taken after the kilonova faded below our detection limits as subtraction references. Our point spread function fitting. We use images taken after the kilonova faded below our detection limits as subtraction references. Our point spread function fitting. We use images taken after the kilonova faded below our detection limits as subtraction references. Our point spread function fitting. We use images taken after the kilonova faded below our detection limits as subtraction references. Our point spread function fitting.

Blackbody fits. Kilonovae are expected to display roughly blackbody emission (perhaps with a steeper fall-off at short wavelengths due to line blanketing10,11,12,13). We fitted a blackbody spectrum to each epoch containing data in more than two bands (excluding w-band data) using Markov chain Monte Carlo (MCMC) simulations through the Python emcee package49 (Extended Data Fig. 2). We find that the photospheric radius remains roughly constant during the first few days after peak at a value of about $5 \times 10^{14}$ cm while the temperature declines from about 6,500 K 1.4 days after the peak to about 4,000 K 2.5 days after the peak (Extended Data Fig. 3). We calculate the bolometric luminosity of the blackbody and take that to be the bolometric luminosity of the event.

Comparison to supernova light curves. AT 2017gfo peaks at an absolute magnitude that is fainter than most supernovae, but comparable to that of some type IIb supernovae, and to plateau luminosities of type IIP supernovae (see, for example, ref. 49). However, AT 2017gfo evolves faster than any known supernova. In Extended Data Fig. 4 we compare it to standard type Ia and type Ib/c light curves50,51, as well as to some of the most rapidly evolving supernovae known52,53, SN 2002bj and SN 2010X. We also plot the plateau drop phase of the prototypical type IIP supernova54 SN 1999em. Type IIP supernova light curves have an approximately 100-day plateau, followed by a rapid drop in luminosity as the power source changes from shock heating to radioactive decay of $^{56}$Co. Still, this sharp decline is slower than the decline in AT 2017gfo. In Extended Data Fig. 4 we also plot the DLT40 and ATLAS non-detection pre-discovery limits55,56 of AT 2017gfo, which further rules out type IIP supernova origin.

Fits to analytical kilonova models. The basic predictions for the peak time, luminosity and temperature of a kilonova, assuming a spherically symmetric, uniform mass distribution for an ejecta in homogeneous expansion, are:

$$t_{\text{peak}} \approx 4.9 \text{ days} \times \left(\frac{M_{\text{ej}} \cdot 2}{v_{\text{ej}}}\right)^{3/2}$$

(1)

$$L_{\text{peak}} \approx 2.5 \times 10^{46} \text{ erg s}^{-1} \times \left(\frac{M_{\text{ej}} \cdot 2}{v_{\text{ej}}}\right)^{-\alpha/2}$$

(2)

$$T_{\text{peak}} \approx 2, 200 \text{ K} \times \left(\frac{M_{\text{ej}} \cdot 2}{v_{\text{ej}}}\right)^{(-\alpha/2)/8} \times \left(\frac{\kappa}{1}\right)^{(-2)/8} \times \left(\frac{\Phi}{1}\right)^{(-1)/8}$$

(3)

where $M_{\text{ej}}$ is the ejecta mass in units of $10^{-2}$ $M_\odot$, $\kappa$ is the opacity of the ejecta mass in units of $10^3$ $cm^2$ g$^{-1}$, $v_{\text{jet}}$ is the ejecta velocity in units of 1 $c$, and $\alpha$ is the power-law index that describes the time dependence of the energy emitted by radioactive decay. Here we use $\alpha = 1.3$, which is typically assumed for r-process decay58. The peak luminosity (see equation (2)) is approximately 1,000 times brighter than a nova, giving kilonovae their name (although some use the more general name ‘macronovae’)54.

These simple relations can reproduce the short rise time and bright peak luminosity deduced from the blackbody fits (Extended Data Fig. 5) with an ejecta mass $M_{\text{ej}}$ of a few hundreds of solar masses and a low ($\kappa < 10^3$ cm$^2$ g$^{-1}$) opacity. However, using these values does not reproduce the observed colours, as it underpredicts the observed temperature (see equation (3)). We use these parameters as starting points for MCMC simulations to fit more sophisticated analytical models52 based on approximations to numerical relativity simulations. We fitted the models to the bolometric light curve rather than using the model bolometric corrections to fit the per-band light curves, since the corrections are only valid for times $\geq 2 \times 10^{-2} M_\odot / M_{\text{ej}}$ after the merger, which would miss much of our data. We fix the heating rate coefficient $\beta = 1.58 \times 10^{14}$ erg s$^{-1}$ and leave the ejecta mass ($M_\odot$), the minimum and maximum ejecta velocities ($v_{\text{min}}$ and $v_{\text{max}}$), the opacity ($\kappa$), and the geometrical parameters ($\theta_{\text{red}}$ and $\Phi_{\text{red}}$) as free parameters. We use the public code provided in ref. 59 for these models and adopt the time-varying thermalization efficiency found in ref. 60. Our MCMC fits converge on an ejecta mass of $(4.0 \pm 0.05) \times 10^{-2} M_\odot$ (1r uncertainties), but do not constrain the ejecta velocities (Extended Data Fig. 6) or the geometrical parameters (in ref. 59 it is demonstrated that in general the geometrical parameters cannot be constrained in this model). We compare the individual band magnitudes from this fit, using the bolometric corrections supplied by the model and find that they are redder than the observations. We conclude that even the more sophisticated analytical models52 (under the stated assumptions for $\kappa$, $\beta$ and the thermalization efficiency) cannot reproduce the colour evolution of our event. As stated for our numerical models21 in the main text, a composition (and hence opacity) gradient or an additional power source, could explain the colour-evolution discrepancy.

Rates. Given the light curve properties reported in the main text, we can explore how many AT 2017gfo-like events are expected to be seen by different optical transient surveys, without relying on a gravitational-wave trigger. The number of kilonovae per year $N$ potentially seen in E epochs by a survey covering a fraction $f$ of the sky down to limiting magnitude $L$ and with cadence $C$ days is:

$$N = \frac{R \times 10^{0.4(L-\text{mag}(C-1)-m_p)}}{(1-C)^{-1}}$$

(4)

where $R$ is the rate of kilonovae per year on the entire sky out to a distance $d$, $\Delta M$ is the decline rate of the kilonova in magnitudes per day, and $m_p$ is the apparent peak magnitude of the kilonova at distance $d$ (we ignore time dilation effects from an expanding Universe). Using the values from our $r$-band data ($m_p = 17$, $\Delta M = 1$ and $R = 1$, we plot the number of detectable kilonovae in Extended Data Fig. 7. We find, for example, that a survey with a limiting magnitude of 21 and sky coverage of 4,000 square degrees with 3-day cadence (similar to the Palomar Transient Factory61,62) would have a two-epoch detection of only one kilonova roughly every 2–3 years. The upcoming Large Synoptic Survey Telescope, reaching a magnitude of 24 on roughly half of the sky with 3-day cadence, could obtain three epochs for one kilonova per year, and two epochs for each of 100 kilonovae per year. Equation (4) demonstrates that increasing the cadence of a survey has a larger effect on kilonova detections than increasing the sky coverage. It is therefore likely that the Large Synoptic Survey Telescope could discover even more kilonovae in its deep drilling survey.

Data availability. The photometric data that support the findings of this study are available in the Open Kilonova Catalog63, https://kilonova.space. Source Data for Fig. 3 are provided with the online version of the paper.
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Extended Data Figure 1 | Timeline of the discovery and the observability of AT 2017gfo in the first 24 h following the merger.
The curved lines denote the airmass and altitude (in degrees above the horizon) of the position of AT 2017gfo on the sky at each LCO Southern Hemisphere site from the start of the night until the hour-angle limit of the LCO 1-m telescopes. The vertical thick lines denote the times when LCO images were obtained (colours correspond to the different filters as denoted in the legend of Fig. 3). AT 2017gfo was observable for approximately 1.5 h at the beginning of the night. Having three Southern Hemisphere sites allowed us to detect the kilonova approximately 6.5 h after the LIGO-Virgo localization, follow it approximately 10 h later, and continue to observe it three times per 24-h period for the following days (Fig. 3). Counterpart announcement is from ref. 31.
Extended Data Figure 2 | Blackbody fits. MCMC parameter distributions (a–f) and spectral energy distributions (luminosity density \( L_\lambda \) as a function of wavelength) with the blackbody fits (g–l) are shown for the six epochs (noted by their modified Julian dates, MJD) with observations in more than two bands after excluding \( w \)-band data. In the parameter distributions, contour lines denote 50% and 90% bounds, the red and blue solid lines overplotted on each histogram denote the mean and median of each parameter distribution (respectively), and the dashed lines denote 68% confidence bounds. Error bars on the luminosity densities denote 1\( \sigma \) uncertainties.
Extended Data Figure 3 | Bolometric luminosity, photospheric radius and temperature deduced from blackbody fits. Error bars denote 1σ uncertainties (n = 200). The large uncertainties in the later epochs might be due to a blackbody that peaks redward of our available data, so these data points should be considered to be temperature upper limits. Our MCMC fits of an analytical model[12] to the bolometric luminosity are shown in blue, and the numerical models[13] from Fig. 3 are shown in red in the top panel. The numerical models were tailored to fit Vriw bands, but not the g band, which is driving the high bolometric luminosity at early times.
Extended Data Figure 4 | AT 2017gfo evolves faster than any known supernova, contributing to its classification as a kilonova. We compare our $w$-band data of AT 2017gfo (red; arrows denote $5\sigma$ non-detection upper limits reported by others\textsuperscript{55,56}) to $r$-band templates of common supernova types (types Ia and Ib/c normalized to peaks of $-19$ mag and $-18$ mag, respectively)\textsuperscript{50,51}, to $r$-band data of two rapidly evolving supernovae\textsuperscript{52,53} (SN 2002bj and SN 2010X) and to $R$-band data of the drop from the plateau of the prototypical type IIP supernova\textsuperscript{54} SN 1999em (dashed line; shifted by 1 mag for clarity).
Extended Data Figure 5 | Peak luminosity and time of AT 2017gfo compared to simple analytical predictions. The parameters from equations (1) and (2) are shown for different values of the ejecta mass $M_{ej}$ (solid lines), the opacity $\kappa$ (dashed lines), and for two different ejecta velocities $v_{ej}$ (red and blue lines). The rise time and peak luminosity of AT 2017gfo (black arrow) can be reproduced by an ejecta velocity $v_{ej} \approx 0.3c$ and a low opacity of $\kappa < 1 \text{ cm}^2 \text{ g}^{-1}$. Matching the data with higher opacities would require higher ejecta velocities.
Extended Data Figure 6 | Parameter distribution for MCMC fits of analytical kilonova models to our bolometric light curve. The contour lines denote 50% and 90% bounds. The red and blue solid lines overplotted on each histogram denote the mean and median of each parameter distribution (respectively). The dashed lines denote 68% confidence bounds. The fits converge on an ejecta mass of \((4.02 \pm 0.05) \times 10^{-2} \text{M}_\odot\) but they do not constrain the velocity (converging on the largest possible range) or the geometrical parameters \((\theta_{ej} \text{ and } \Phi_{ej})\), nor do they reproduce the colour evolution of our event (not shown). This indicates that these models may not be entirely valid for AT 2017gfo (although in ref. 59 it is shown that the geometrical parameters cannot be constrained either way). Our numerical models, on the other hand, which include detailed radiation transport calculations, do provide a good fit to the data (Fig. 3) with \(M_{ej} = (2–2.5) \times 10^{-2} \text{M}_\odot\), \(v_{ej} = 0.3c\), and a lanthanide mass fraction of \(X_{\text{lan}} = 10^{-4.5}\), corresponding to an effective opacity of \(\kappa \lesssim 1 \text{ cm}^2 \text{ g}^{-1}\).
Extended Data Figure 7 | Expected kilonova rates in optical transient surveys. The number of AT 2017gfo-like events per year detectable by $r$-band transient surveys in two (solid lines), three (dashed lines) and five (dotted lines) epochs before fading from view. The numbers of events refer to the entire sky, and should be multiplied by the fraction of sky covered by the survey. We assume that the intrinsic rate of events is one per year out to 40 Mpc (scaling accordingly to larger distances).