Spectroscopic identification of r-process nucleosynthesis in a double neutron star merger

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The merger of two neutron stars is predicted to give rise to three major detectable phenomena: a short burst of γ-rays, a gravitational wave signal, and a transient optical/near-infrared

source powered by the synthesis of large amounts of very heavy elements via rapid neutron capture (the r-process)[1–3]. The latter transients, named "macronovae" or "kilonovae" (refs 4-7), are believed to be cradles of production of rare elements like gold and platinum[8]. The most compelling evidence to date for a kilonova was a very faint near-infrared rebrightening in the afterglow of a short γ-ray burst[9,10] at $z = 0.356$, although suggestive findings of bluer events have been reported[11]. Here we report the spectral identification and describe the physical properties of a bright kilonova associated with the gravitational wave source GW 170817 (The LIGO Scientific Collaboration & the Virgo Collaboration, 2017, in prep.) and γ-ray burst GRB 170817A (Goldstein et al., 2017, Astrophys. J. L., submitted; Savchenko et al., 2017, Astrophys. J. L., submitted) associated with a galaxy at a distance of 40 Mpc. Using a comprehensive spectral series from ground-based observatories covering the ultraviolet through the near-infrared wavelength range, we find that the kilonova can be characterized by rapidly expanding ejecta with spectroscopic features similar to those predicted in current models[12,13]. The ejecta are optically thick early on after merger and move with ∼0.2c, reaching a radius of ~ 50 AU in only 1.5 days. As the ejecta expand, atomic species imprint broad absorption-like lines on the spectral continuum, the products of nucleosynthesis occurring in a post-merger fast-moving (0.2c) dynamical ejecta and two slower (0.05c) wind regions. Comparison with spectral models suggests the merger ejected 0.03–0.05 solar masses, including high-opacity lanthanides.

GW170817 was detected on Aug 17, 12:41:04 UT (The LIGO Scientific Collaboration & the Virgo Collaboration, 2017, in prep.). A weak short duration ($t \sim 2s$) GRB in the GW error area triggered the Fermi-GBM about two seconds later (Goldstein et al., 2017, Astrophys. J. L., submitted), and was detected also by the INTEGRAL SPI-ACS (Savchenko et al., 2017, Astrophys. J. L., submitted). A significantly improved sky localization was obtained from the joint analysis of LIGO and Virgo data of the GW event, with a 90% error region of 33.6 square degrees (The LIGO Scientific Collaboration & the Virgo Collaboration, 2017, in prep.). Following this joint GW/GRB detection, a world-wide extensive observational campaign started, using space and ground-based telescopes to scan the sky region were the events were detected. A new point-like optical source, named SSS17a/DLT17ck (coordinates RA(J2000) = 13:09:48.09, Dec(J2000) = -23:22:53.3) was rapidly reported (see Coulter et al., 2017, in prep. and Valenti et al., 2017, in prep.), located at 10 arcsec from the center of the S0 galaxy NGC 4993 ($z = 0.00968$[14]) in the ESO 508-G018 group at a distance of 40 Mpc, consistent with the luminosity distance of the GW signal.

We carried out targeted and wide field optical/NIR imaging observations of several bright galaxies within the reconstructed sky localization of the GW signal with the Rapid Eye Mount (REM) telescope and with the ESO VLT Survey Telescope (ESO-VST). This led to the detection of SSS17a in the REM images of the field of NGC 4993 obtained 12.8 hours after the GW/GRB event. Following the detection of this source, we started an imaging and spectroscopic follow-up campaign at optical and NIR wavelengths. Imaging was carried out with the REM, ESO-VST and ESO-VLT telescopes. A series of spectra was obtained with the VLT/X-shooter, covering the wavelength range 3200–24800 Å with VLT/FORS2, covering 3500–9000 Å, and with Gemini-S/GMOS covering 5500-9000 Å (see Kasliwal et al., 2017, Science submitted) for GMOS reduction and analysis details). Overall, we observed the source with an almost daily cadence during the period Aug 18 – Sep 02, 2017 ($\sim$ 0.5–15.5 days after the GW/GRB trigger; details are provided in the Methods section). We present here the results of the observations carried out in August 2017.

As described in the following, the analysis and modelling of the spectral characteristics of our dataset, together with their evolution with time, result in a good match with the expectations for kilonovae, providing the first compelling observational evidence for the existence of such elusive transient sources. Details of the observations are provided in the Methods section.

We adopted a foreground Milky-Way extinction of E($B - V$) = 0.1 mag and the extinction curve of[15], and used this to correct both magnitudes and spectra (see Methods). The extinction within the host galaxy is negligible, based on the absence of significantly detected characteristic narrow absorption features associated with its interstellar medium. The optical light curve resulting from our data is shown in Figure 1 and the sequence of X-shooter, FORS2, and GMOS spectra in Figure 2. Apart from Milky Way foreground lines the spectrum is otherwise devoid of narrow features that could indicate association with NGC 4993. In the slit, displaced from the position of the transient from $3''$–$10''$ (0.6–2.0 kpc in projection), we detect narrow emission lines exhibiting significant structure, both spatially and in velocity space (receding at 100–250 km/s with respect to the systemic velocity) likely caused by the slit crossing a spiral structure of the galaxy (see Methods).

The first X-shooter spectrum of the transient shows a bright, blue continuum across the entire wavelength coverage – with a maximum at $\sim$6000 Å and total luminosity of 3.2×10^{41} erg s^{-1} – that can be fit with a black-body of temperature 5000 ± 200 K, and a spherical equivalent radius of

$\sim 8 \times 10^{14}$ cm. At a phase of 1.5 days after the GW/GRB trigger, this implies an expansion velocity of the ejected material of $\sim 0.2c$. The temperature is considerably lower than that inferred from photometric observations about 20 hours earlier ($\sim 8000\,\mathrm{K}$)[16], suggesting rapid cooling. On top of this overall black-body shape are undulations that may represent very broad absorption features similar to those suggested in merger ejecta simulations[13]. We refrain from connecting these to expansion velocity as they may be blends of many lines with poorly known properties.

In the second epoch, one day later, where the spectrum only covers the optical range, the maximum has moved to longer wavelengths, indicating a rapid cooling. At the third epoch, when information is again available also at NIR wavelengths, the peak has shifted still to 11000 Å, and the overall spectral shape is quite different, indicating that the photosphere is receding, the ejecta are becoming increasingly transparent, and more lines become visible. The NIR part of the spectrum evolves in flux and shape much less rapidly. Spectrally broad absorption features are observed ($\Delta\lambda/\lambda \sim 0.1 - 0.2$). We exclude that these rapid changes can be compatible with supernova time evolution and are instead consistent with a kilonova (see Methods and Extended Data Figure 2).

Unlike in the case of supernova absorption lines, the identification of kilonova atomic species is not secure. The neutron-rich environment of the progenitors suggests r-process nucleosynthesis as the mechanism responsible for the elemental composition of the ejecta. Lacking line identification, various plausible nuclear reaction networks are considered and included in models of radiative transfer of kilonova spectrum formation. A fraction of the synthesized atoms are radioactive: while decaying they heat the ejecta, which then radiate thermally. All atomic species present in the ejecta with their various degrees of excitation and ionization absorb the continuum and cause the formation of lines. The models aim at reproducing these lines assuming a total explosion energy, a density profile and an ejecta abundance distribution. In kilonovae it is often envisaged that nucleosynthesis takes place in different regions with different neutron excesses and ejecta velocities, typically a post-merger dynamical ejecta region and a disk-wind region.

Various models predict different components and different synthesized masses. Tanaka et al. (2017) presented three models with different electron/proton fractions Y_e (see Methods). We compare our spectra with a scenario where these three components contribute to the observed spectra (Figure 3): a lanthanide-rich dynamical ejecta region with a proton fraction in the range Y_e = 0.1–0.4 and a velocity of 0.2c (orange in Fig. 3), and two slow (0.05c) wind regions of which one has Y_e = 0.25 and mixed (lanthanide-free and lanthanide-rich) composition (green) and one has Y_e = 0.30 and is lanthanide-free (blue). Each of these spectra falls short of the observed luminosity by a factor of $\sim$2, while for other predictions[5,12] the discrepancy is an order of magnitude. In order to investigate the applicability of the model to the present, more luminous, case we have assumed that the involved ejecta mass is larger. By decreasing the high Y_e (0.3) wind component to 30% of the value in the original model, and increasing both the intermediate Y_e (0.25) wind component and the contribution of the dynamical ejecta nucleosynthesis by a factor of 2 we obtain a satisfactory representation of the first spectrum (Figure 3).

Although direct rescaling of these models is not in principle correct (for larger masses we can expect that the spectrum of each ejecta could change) we can estimate that the ejected mass was $\sim$

0.03 – 0.05 $M_\odot$, and that the high Y_e wind ejecta (blue line) are significantly suppressed, possibly because of viewing angle away from the GRB or a narrow jet angle or both. It is also suggestive that a wide range of Y_e values are realised in the ejecta, possibly as a function of latitude.

At successive epochs, the same components represent in a less satisfactory way the observed spectral features, which indicates that the set of adopted opacities is not completely adequate, as the cooling of the gas is not properly followed by lines of different ionization states, and that the radioactive input may also not be accurately known.

As a short GRB was detected in association with a GW trigger, we evaluated the expected contribution of its afterglow at the epochs of our observations. Nine days after GW170817 trigger time, an X-ray source was discovered by Chandra at a position consistent with the kilonova, at a flux level of $\sim 4.5 \times 10^{-15}$ erg cm^{-2} s^{-1} (0.3–8 keV). This source could be delayed X-ray afterglow emission from GRB170817A, produced by an off-beam jet (Troja, Piro, Van Eerten et al., 2017, in prep.). This may account for the otherwise small probability of having an aligned short GRB jet within such a small volume[17]. The X-ray emission is compatible with different scenarios: a structured jet with an energy per solid angle decreasing with the angular distance from the axis, viewed at large angles (e.g.[18]), a cocoon accelerated quasi–isotropically at mildly relativistic velocities by the jet[19,20] or a simple uniform jet observed at large angles. All these scenarios predict an optical afterglow much fainter than the kilonova (see Methods). On the other hand, if we assume that the early (0.45 days) optical flux we measured is afterglow emission, we estimate, at the same epoch, an X-ray flux $> 10^{-12}$ erg cm^{-2} s^{-1} and a 6 GHz radio flux density of ≈ 10 mJy. These estimates are not consistent with the absence of X-ray and radio detections at the corresponding epochs[21] (Evans et al., 2017, Science, submitted).

Our long and intensive monitoring and wide wavelength coverage enabled the unambiguous detection of time-dependent kilonova emission and sampled fully its time evolution. This not only confirms the association of the transient with the GW, but, combined with the short GRB detection, also proves beyond doubt that at least a fraction of short duration GRBs are indeed associated with compact star mergers. Furthermore, this first detection provides important insights on the environment of merging NSs. The counterpart's location is only ~ 2 kpc (projected distance) away from the center of an early-type galaxy. This is a quite common offset for short GRBs (e.g.[22]) and is consistent with predictions from theoretical models of merging NSs (e.g.[23]). Moreover, the counterpart's location does not appear to coincide with any globular cluster, which suggests a field origin for this NS binary. The nearest possible globular clusters are at $> 2.5''$ (corresponding to 500 pc) from the source position (Levan et al. in prep.). The formation channel of this event would be best explored with future modeling and simulations. Finally, since this GRB was rather under-energetic (isotropic gamma-ray output of $\sim 10^{46}$ erg) and likely off-axis with respect to the line of sight, we conclude that there may be a large number of similar nearby off-axis short bursts that are not followed up at frequencies lower than gamma-rays. These are also GW emitter candidates and the present event has demonstrated how the search of the randomly oriented parent population of short GRBs can be made effective via coordinated gravitational interferometry and multi-wavelength observations.

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Acknowledgements Work in this paper was based on observations made with ESO Telescopes at the Paranal Observatory under programmes ID 099.D-0382 (PI: E.Pian), 099.D-0622 (PI: P: D'Avanzo), 099.D-0191 (PI: A. Grado) and with the REM telescope at the ESO La Silla Observatory under program ID 35020 (PI: S. Campana). We thank the ESO Director General for allocating Discretionary Time to this program and the ESO operation staff for excellent support of this program. We acknowledge INAF for supporting the project "Gravitational Wave Astronomy with the first detections of adLIGO and adVIRGO experiments - GRAWITA" PI.: E. Brocato. We acknowledge support from the ASI grant I/004/11/3. J. Hjorth was supported by a VILLUM FONDEN Investigator grant (project number 16599).

Author contribution This effort was led by the GRAvitational Wave Inaf TeAm (GRAWITA), and is based on GW electromagnetic follow-up programs at ESO and at many telescopes both in Italy and at the Canary Islands. All authors have shared the work and contributed to its development at many phases from preparation of proposals, coordination with the LIGO-VIRGO collaborations, activation of approved programs at many facilities, data acquisition, reduction, analysis, interpretation and presentation. E. Pian and P. D'Avanzo are PIs of the two active ESO VLT programs and coordinated the work. S. Campana coordinated the REM observations. J. Selsing reduced all the X-shooter data and wrote the relevant sections. E. Cappellaro assisted with the analysis. S. Covino, A. Grado and A. Melandri reduced and analysed the optical photometry. M. Tanaka developed the kilonova spectral models and P. Mazzali wrote the part on their description and discussion. G. Ghirlanda, G. Ghisellini and O. S. Salafia wrote the section on the off-beam jet with useful contributions from Y.Z. Fan, Z.P. Jin and T. Piran. D. Watson assisted with the analysis of spectra in light of thermal models and assisted with paper writing. E. Brocato was the Principal Investigator of the GRAWITA consortium that led to these results. M. Branchesi played a central role in driving the GRAWITA activities. She participated in the organization of the observations, interpretation of the data, and discussed and commented the paper. A. Grado coordinated the ESO-VST observations. L. Limatola, F. Getman developed the pipeline to reduce the VST data. C. Kouveliotou assisted with paper writing and a number of practical issues. L. Nicastro supervised the informatics and participated in the scientific discussion. S. Piranomonte and V. D'Elia contributed to the data reduction and analysis of the X-shooter spectra. E. Palazzi, A. Rossi, G. Stratta and G. Greco participated in the organization of the observations, data analysis and interpretation. L. Tomasella, S. Yang, and S. Benetti contributed to the data analysis, interpretation of the spectral features and observation plans.

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The authors declare that they have no competing financial interests.

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Figure 1: Multiband optical light curve of SSS17a/DLT17ck. The data reported in Extended Data Table 1 are shown (filled symbols). The data were not corrected for Galactic reddening.

Figure 2: Time evolution of the SSS17a/DLT17ck spectra. VLT X-shooter, FORS2, and GMOS spectra (phases with respect to explosion are as in Extended Data Table 2; the flux normalization is arbitrary). Spikes and spurious features were removed and a filter median of 21 pixels was applied. The data were not corrected for Galactic reddening.

Figure 3: Kilonova model compared to the SSS17a/DLT17ck spectra X-shooter spectra at the first four epochs and kilonova models overlaid: dynamical ejecta (Y_e = 0.1-0.4, orange), wind region with Y_e = 0.3 (blue) and Y_e = 0.25 (green). The burgundy curve represents the sum of the three model components.

Methods

Optical/NIR imaging Our first observations of the field of SSS17a were carried out with the 60-cm robotic telescope REM[31] located at the ESO La Silla Observatory (Chile) in the g, r, i, z and H bands starting on 2017 Aug 18 at 01:29:28 UT (i.e. 12.8 hours after the GW event). The field was included in the selection we made to carry out targeted observations of catalogued galaxies in the LVC skymap aimed at searching for an optical/NIR counterpart of the GW event starting on 2017 Aug 17 at 23:11:29 UT (i.e. 10.5 hours after the GW event)[32,33]. Following this first detection, we started an extensive follow-up campaign of optical/NIR imaging carried out with an almost daily cadence from about 1.5 to 15.5 days after the time of the GW trigger. These observations were performed using the ESO VLT telescopes equipped with the X-shooter acquisition camera, the FORS2 instrument, and the ESO VST equipped with OmegaCam instrument[34–37]. The complete log of our photometric observations is reported in Extended Data Table 1. The optical/NIR light curves are shown in Figure 1. Concerning REM and FORS2 imaging, data reduction was carried out following the standard procedures: subtraction of an averaged bias frame and division by a normalized flat frame. The astrometric solution was computed against the USNO-B1.0 catalogue (`http://www.nofs.navy.mil/data/fchpix/`). Aperture photometry was performed using SExtractor[38] and the PHOTOM package part of the Starlink software distribution (`http://starlink.eao.hawaii.edu/starlink`). The photometric calibration was achieved by observing Landolt standard fields and the Pan-STARRS catalogue (`https://panstarrs.stsci.edu`). In order to minimize any systematic effect, we performed differential photometry with respect to a selection of local isolated and non-saturated reference stars. As shown in Extended Data Figure 1, the transient is embedded in the host galaxy light, so that the background around the transient position is highly inhomogeneous, making accurate photometry measurements arduous. In order to minimize the effect of flux contamination from the host light, we fitted it with an analytical profile. The result obtained from the fit was then subtracted from the image in a neighborhood of the transient. This procedure was repeated for each frame. After this subtraction, the background around the transient position is much more uniform, enabling accurate photometric measurements. A dedicated procedure was applied for the reduction and analysis of the wide-field images obtained with the VLT Survey Telescope (VST[39]). The telescope is equipped with OmegaCam [40], a camera with one square degree field of view (FOV) matched by 0.21 arcsec pixels scale. Data have been processed with a dedicated pipeline for the VST-OmegaCAM observations (dubbed VST-tube[41]). The pipeline searches for new data in the ESO Data archive and, if available, automatically downloads and processes them performing the following main steps: pre-reduction; astrometric and photometric calibration; mosaic production. The OT magnitude, in the AB system, is the PSF fitting magnitude measured on the image after subtracting a model of the galaxy obtained fitting the isophotes with the IRAF/STSDAS task ELLIPSE [42]. The reference catalog used for the absolute photometric calibration is the APASS DR9.

FORS2 spectroscopic observations FORS2 spectra were acquired with the 600B and 600RI grisms, covering the 3500–8600 Å wavelength range. We used in all cases a $1''$ slit, for an effective resolution of $R \sim 800 - 1000$. Spectral extraction was performed with the IRAF software package (IRAF is the Image Reduction and Analysis Facility made available to the astronomical community by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under contract with the US National Science Foundation. It is available at http://iraf.noao.edu.). Wavelength and flux calibration of the spectra were accomplished using helium-argon lamps and spectrophotometric stars. A check for slit losses was carried out by matching the flux-calibrated spectra to our simultaneous photometry (see Extended Data Table 1 and Extended Data Table 2). This shows that the derived spectral shape is robust.

X-shooter spectroscopic observations The cross-dispersed echelle spectrograph, X-shooter[43], mounted on the VLT, was used to observe the optical/near-infrared counterpart of GW170818. The observing campaign started on the night following the discovery and continued until the source had faded below the detection limit (see Extended Data Table 2) of X-shooter. The observations were carried out using a standard ABBA nodding pattern. Similar position angles of the slit were used for all observations. The position of the slit on the source is shown in Extended Data Figure 1.

The spectroscopic data obtained with X-shooter were managed with the Reflex interface[44] and reduced using version 2.9.3 of the X-shooter pipeline[45]. The reduction cascade consists of bias subtraction, order tracing, flat fielding, wavelength calibration, flux calibration using the spectrophotometric standard EG274 [46], background subtraction and order rectification – all carried out using the nightly obtained calibration files. A refinement to the wavelength solution was obtained by cross correlating the observed sky spectra with a synthetic sky spectrum[47,48], leading to a wavelength solution more accurate than 1 km s^{-1}. Because X-shooter is a cross-dispersed echelle spectrograph, the individual echelle orders are curved across each detector and a rectification algorithm, which correlates neighboring pixels, must be employed. A sampling of 0.2/0.2/0.6

Å per pixel (in the UVB, VIS, and NIR arms, respectively) in the rectified image was chosen to minimize this correlation while conserving the maximal resolving power. The effective resolving power, R, of each observation was obtained from fits to unsaturated telluric absorption lines and yielded mean values of 4290/8150/5750 in the UVB/VIS/NIR arms, respectively. This is better than nominal values, owing to a seeing PSF being narrower than the slit width. Immediately following the observations each night, telluric standard stars were observed at an airmass comparable to the target from which the atmospheric transmission spectrum was obtained using Molecfit[49,50]. Host continuum contamination is visible as a faint background gradient along the slit. An effort has been made to minimize this contamination by using the background regions closest to the target. The images are combined in nightly sets using a weighting scheme based on a moving background variance measure wide enough to avoid it being pixel based and therefore unsuitable for Poisson-noise dominated images. For a subset of the observations, the signal-to-noise (S/N) in the spectral trace is large enough to build a model of the spectral line-spread function to employ an optimal extraction algorithm [51], but for the majority of the data, an aperture covering the entire trace is used. To establish an accurate flux calibration, slit loss corrections were calculated using the average seeing FWHM of the nightly observations along with the theoretical wavelength dependence of seeing [52]. The slit losses are obtained by integrating a synthetic 2D PSF over the width of the slits and corrections are made accordingly.

Foreground dust extinction We have estimated the intervening dust extinction toward the source using the Na I D line doublet at 5896 Å. Based on the strength of the line in our Galaxy we derive E($B - V$) = 0.09 mag using component D1, E($B - V$) = 0.05 mag using component D2, and

E$(B-V)$ = 0.06 mag using the sum[53]. The Galactic extinction is thus limited to E$(B-V) <$ 0.1 mag. Similar upper limits on E$(B-V)$ are obtained from the upper limits on the equivalent widths of the undetected K I 7699 Å absorption line[54] (EW $<$ 0.025 Å) and undetected 8620 Å diffuse interstellar band[55] (EW $<$ 0.04 Å). These estimates and limits are marginally consistent with the value of E$(B-V)$ = 0.11 mag obtained from COBE/DIRBE maps covering that sky region[56].

Spectrum analysis and interpretation The first epoch X-shooter spectrum was fit with a black-body with temperature of 5000 ± 200 K. The main deviations from this fit are two absorption-like lines at 8100 and 12300 Å, that evolve with time and become more pronounced in the second spectrum. Altogether, all deviations from a black-body in the first spectrum are below $\sim$10% from 3500 Å to 20000 Å, indicating that the fit is very satisfactory. Moreover, the expansion speed of $0.2c$ we derive from the black-body radius at the epoch of the first spectrum (1.5 days) is compatible with the width of the absorption lines we observe in the second spectrum ($\Delta\lambda/\lambda \sim 0.1-0.2$), confirming that the black-body emission in the first spectrum is highly efficient.

The first 4 X-shooter spectra were compared with kilonova models from Tanaka et al. (2017). The model uses atomic structure calculations for Se (Z = 34), Ru (Z = 44), Te (Z = 52), Ba (Z = 56), Nd (Z = 60), and Er (Z = 68) to construct the atomic data for a wide range of r-process elements. By using two different atomic codes, they confirmed that the atomic structure calculations returned uncertainties in the opacities by a factor of up to $\sim$2. Thereafter, they apply multiwavelength radiative transfer simulations to predict a possible variety of kilonova emission. For each model, the abundance is assumed to be homogeneous in the ejecta, However, a high-Y_e component should preferentially dominate near the polar region and low-Y_e/dynamical component develops in the equatorial region. For each model, the energy release is similar to a power-law ($t^{-1.3}$) owing to the sum of the radioactive decays of various nuclei with different lifetimes. The efficiency of the energy deposition is also taken into account, and the energy deposition rate is somewhat steeper than $t^{-1.3}$ because the gamma-rays can escape without depositing energy.

We emphasize that we have not attempted a real fit of this model to our X-shooter spectra, but have rather looked into an interpretation that was in reasonable agreement. The match is satisfactory only for the first X-shooter spectrum, and not completely satisfactory for the following three. For this reason, we refrained from deriving a light curve model. Infact, in principle, one may fold the synthetic spectral model with the sensitivity curve of any given broad-band filter and integrate the flux in the corresponding band to compare with the observed one. However, the result may be misleading independent of how persuasive it is at face value. The spectral comparison allows one to appreciate in which wavelength ranges the model is effective and in which ones it fails. Integration of the model over a broad wavelength interval cancels the spectral ”memory” and prevents a critical judgment. In other words, since the spectral model is not completely satisfactory, the comparison of synthetic and observed photometry is not significant, although it may appear good.

Description of the spectral evolution The first X-shooter spectrum obtained at $t = 1.5$ d after the GW trigger shows an almost featureless, moderately blue continuum. The overall spectral energy distribution is similar to that of early, broad line core collapse SNe. While in general at this relatively low temperature (∼5000 K) SNe typically show strong broad features using the supernova spectral classification tool GELATO [57] a good match is obtained with the early spectra of the type Ib SN2008D/XRF080109[58]. As shown in Extended Data Figure 2, the X-shooter extended spectral range displays, by comparison with the black-body fit (dotted line) the presence of some large scale modulations that are suggestive of multi-component contributions already suggestive of a kilonova event.

In the next two days the spectrum shows a very rapid evolution. The continuum temperature rapidly drops to about 3300K and broad features emerges, with peaks at 10700 Å and 16000 Å. The broad features point to very high expansion velocity and the rapid evolution to a low ejected mass. The combined spectral properties and evolution are unlike those of any known SN types and instead they are very similar to the predicted outcomes of kilonova models.

In the following week the temperature derived from the optical continuum seems to remain roughly constant while the peak at 10700 Å drifts to longer wavelengths (11200 Å at day 6) and decreases in intensity until, at ten days from discovery, the dominant feature in the spectrum is a broad emission centered at about 21000 Å.

Host emission analysis Extending 3–10″ (0.6 – 2.0 kpc in projection) from the position of the GW counterpart are emission lines formed in the host. The lines are identified as [O II]$\lambda 3726, 3729$, Hβ, [O III]$\lambda 4959, 5007$, Hα, [N II]$\lambda 6549, 6583$ and [S II]$\lambda 6717, 6731$, and they exhibit both spatial and velocity structure along the extent of the slit, as shown in Extended Data Figure 3.

From the brightest blob of emission, centered at 6″ (1.2 kpc in projection) from the source, we measure a receding velocity of $247 \pm 15\,\mathrm{km\,s^{-1}}$ relative to the host nucleus (adopting a systemic velocity of NGC 4993 of $2916 \pm 15\,\mathrm{km\,s^{-1}}$). Along the spatial direction of the slit, closer to the source, the emission line centroids become more blue-shifted, approaching a recession velocity of $100\,\mathrm{km\,s^{-1}}$ relative to the NGC 4993 systemic velocity. The velocity range ($150\,\mathrm{km\,s^{-1}}$) of the line emission along the slit indicates coherent motion of the gas along the slit. This is further supported by the dust lanes visible superposed on the host nucleus, see Extended Data Figure 3.

which extends outwards and curls clockwise around the nucleus and intersects the slit at the position of the line emission. This means that NGC 4993 either has trailing spiral arms and is rotating counter-clockwise or leading spiral arms and rotating clock-wise. The presence of spiral arms was also noted by[59]. A strong [N II]λ6583 relative to Hα combined with a weak Hβ relative to [O III]λ5007 indicates a radiation field dominated by AGN activity, as also reported previously (Kasliwal et al., 2017, Science, submitted; Hallinan et al., 2017, in prep.; Cooke et al., 2017, in prep.) and supported by the presence of a central radio source (Alexander et al., 2017, in prep.). Using the Balmer decrement, the inferred extinction at the position of the line emission is E($B-V$) $= 0.21 \pm 0.21$.

Off–beam jet scenario GRB170817A had a fluence of 2.2×10^{-7} erg cm^{-2} in the 10-1000 keV energy range as observed by the GBM which, at a distance of 40 Mpc, corresponds to a γ–ray isotropic equivalent energy $E_{\rm iso} \sim 4.3 \times 10^{46}$ erg. The peak energy is $E_{\rm peak} = 128 \pm 48$ keV[?,60]. The observed $E_{\rm iso}$ is three to four orders of magnitude smaller than the average energy of short GRBs with known redshift[61,62].

For illustration let us consider a very simple model: a uniform conical jet of semi-aperture angle $\theta_{\rm jet}$ observed off–beam, i.e at a viewing angle $\theta_{\rm view} > \theta_{\rm jet}$. In this case larger bulk Lorentz factors Γ correspond to larger de–beaming factors $b = E_{\rm iso}(0^\circ)/E_{\rm iso}(\theta_{\rm view})$ for a fixed $\theta_{\rm view}$[63,64]. Given the small distance of 40 Mpc, and a likely luminosity function decreasing with increasing luminosity (e.g. [65,66]), we can assume that the on–axis luminosity of this burst belongs to the low–luminosity tail. For this reason we assume $E_{\rm iso}(0^\circ) = 10^{50}$ erg. Therefore $b = 2500$. The probability of a jet oriented at an angle $< \theta_{\rm view}$ is $P(< \theta_{\rm view}) = 1 - \cos\theta_{\rm view}$. A probability of at least $P > 10\%$ implies $\theta_{\rm view} > 26^\circ$. An off-axis viewing angle larger than $\sim 30^\circ$ is also suggested by the expected rate of joint GW and Fermi-GBM detection[17] rescaled to the actual observations. Combining Eq. 2 and 3 from[63] it is possible to estimate the observed energy $E_{\rm iso}$ and peak energy $E_{\rm peak}$ as a function of $\theta_{\rm view}$ and Γ for a given $\theta_{\rm jet}$. With $\theta_{\rm view} = 30^\circ$, $b = 2500$ ($E_{\rm iso}(0^\circ) = 10^{50}$ erg) requires $\Gamma = 10$ for $\theta_{\rm jet} = 10^\circ$. The latter is within the currently few estimates of short GRB opening angles[67] and $\Gamma \sim 10$ is within the dispersion of the $\Gamma - E_{\rm iso}$ relation[68,69] for $E_{\rm iso}(0^\circ) \sim 10^{50}$ erg. With these values $E_{\rm peak}(0^\circ)$ turns out to be $\sim$2 MeV. The corresponding comoving frame peak energy would be $\sim$100 keV. If photons with much larger energies are absorbed by pair production we should expect (as observed at 30°) a spectral cutoff at $\sim$650 keV which is larger than the observed peak energy reported by the GBM. Though these values of $E_{\rm peak}(0^\circ)$ and $E_{\rm iso}(0^\circ)$ are consistent with those observed in short GRBs, they locate this burst relatively far from the possible spectral-energy correlations of short GRBs.

Extended Data Figure 4 shows the predicted afterglow light curves at 6 GHz (red), R band (green) and 1 keV (blue). The cyan symbol shows the X–ray flux at 15 days (Troja, Piro, Van Eerten et al., 2017, in prep.; Haggard et al., 2017, in prep.). The orange arrows show two representative radio upper limits: at 8.65 days (obtained[71] by co-adding six e-MERLIN observations at 5 GHz) and at 20 days (obtained[72] with MeerKAT at 1.5 GHz). For the model curves the assumed parameters are: $\theta_{\rm jet} = 10°$, $\theta_{\rm view} = 30°$, isotropic equivalent kinetic energy $E_{\rm k,iso} = 10^{50}$ erg, $\Gamma = 10$, a uniform density ISM with $n = 2 \times 10^{-3}$ cm^{-3} and standard micro-physical parameters at the shock i.e. $\epsilon_{\rm e} = 0.1$, $\epsilon_{\rm B} = 0.01$ and electrons' energy injection power law index $p = 2.1$. Standard afterglow dynamics and radiation codes[70] are used. As can be seen the R flux is always below 2×10^{-5} mJy, corresponding to R>28, and therefore orders of magnitude lower than the kilonova emission.

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Data Availability: The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Extended Data Table 1: Log of photometric observations. [a]JD - 2,400,000.5; [b]After GW trigger time; [c]AB magnitudes, not corrected for Galactic extinction (E_{B-V}=0.11).

Extended Data Table 2: Log of spectroscopic observations. [a] UT days of Aug 2017. [b] JD - 2,400,000.5. [c] After GW trigger time. [d] Fluxes at 6000 and 15000 Å in 10^{-18} erg s^{-1} cm^{-2} $Å^{-1}$, not corrected for reddening; uncertainties are $\sim$10%.

Extended Data Figure 1: Image of the NGC4993 galaxy. The image was obtained with the X-shooter acquisition camera (z filter). The X-shooter slit overlaid in red. The position of the OT has been marked by a blue circle. The position of the line emission in the slit has been also marked. The dust lanes visible in the host intersects the slit at the position of the line emission.

Extended Data Figure 2: Black-body fit to the SSS17a/DLT17ck spectra. The two early X-shooter spectra of GW170817, obtained 1.5 and 3.5 d after discovery are compared with the spectra of the type Ib SN 2008D[58] obtained at 2-5 days after explosion respectively (blue, arbitrarily scaled in flux). The dotted line show the black-body fit of the optical continuum of GW170817 with temperature 5000 and 3200 K respectively.

Extended Data Figure 3: 2D image of the SSS17a/DLT17ck spectrum. The upper panel shows the rectified, X-shooter 2D-image. The dark line visible across the entire spectral window is the bright continuum of the OT and the offset, dark blobs indicate the position of the line emission from NIIλ6549, Hα, and NIIλ6583. The lower panel shows an extraction of the line emission where the line fits are overlain. The integrated line fluxes are given in the labels, normalized by a factor of 10^{-17} for clarity.

Extended Data Figure 4: Off-axis GRB afterglow modeling. Synthetic X-ray, optical and radio light curve of the GRB afterglow as predicted in an off-axis jet model. The filled dot symbol shows the X-ray detection (Troja, Piro, Van Eerten et al., 2017, in prep.) and the arrows two representative radio upper limits [71,72].