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NEUTRON STAR MERGER

Compact radio emission indicates a structured jet was produced by a binary neutron star merger

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The binary neutron star merger event GW170817 was detected through both electromagnetic radiation and gravitational waves. Its afterglow emission may have been produced by either a narrow relativistic jet or an isotropic outflow. High-spatial-resolution measurements of the source size and displacement can discriminate between these scenarios. We present very-long-baseline interferometry observations, performed 207.4 days after the merger by using a global network of 32 radio telescopes. The apparent source size is constrained to be smaller than 2.5 milli–arc seconds at the 90% confidence level. This excludes the isotropic outflow scenario, which would have produced a larger apparent size, indicating that GW170817 produced a structured relativistic jet. Our rate calculations show that at least 10% of neutron star mergers produce such a jet.

The binary neutron star merger GW170817 was detected in both gravitational waves (GWs) (*1*) and electromagnetic (EM) emission (*2*). Less than 2 s after the detection of the GW signal, a weak short duration γ-ray burst (GRB 170817A) was observed (*3*, *4*). Eleven hours later, electromagnetic observations from ultraviolet to near-infrared wavelengths (*2*) pinpointed the host galaxy as NGC 4993, at ~41 Mpc distance. The temporal and spectral properties of this emission component reflect those expected for a kilonova, the radioactive decay–powered emission from material ejected during and after a neutron star merger (*5*, *6*). Nine and 16 days after the GW event, x-ray (*7*, *8*) and radio (*9*) emissions were detected. These are interpreted as the afterglow of GRB 170817A. Monitoring of the afterglow with radio, optical, and x-ray telescopes showed a slow achromatic increase in flux ($F \propto t^{0.8}$, where F indicates the flux and t indicates the time elapsed since GW170817) (*10*) until ~150 days after the merger (*11*–*13*). After this epoch, the flux began to decrease (*14*, *15*).

Interpretation of the long-lived radio, optical, and x-ray emission has suggested the launch of a jet from the remnant of the merger. The jet drills into the surrounding kilonova material that was ejected shortly beforehand. Either the jet successfully breaks through the ejecta, developing an angular structure [the energy and velocity scale with the angular distance θ from the jet axis (*16*)], or it fails to break out, depositing all its energy into the ejecta and forming a hot cocoon, which subsequently expands because of its high pressure (*17*–*20*). In the latter case, the energy is expected to be distributed over a wide opening angle, and the expansion velocity is expected to be lower with respect to the jet scenario. Owing to the angular structure, the successful jet scenario is often called a structured jet (*21*, *22*), whereas the unsuccessful jet scenario is sometimes referred to as a choked jet or cocoon.

The x-ray, optical, and radio brightness as function of time (light curve) of GRB 170817A up to ~230 days (*15*, *23*) does not distinguish the two scenarios; with reasonable parameters, both models are consistent with those observations. Independent constraints on the geometry of the relativistic outflow can be obtained through polarization measurements and/or interferometric imaging (*24*–*27*). Because of the higher velocity and narrower opening angle, a structured jet is expected to have a larger displacement from the merger location and, at ~200 days, is predicted to be compact, with an angular size smaller than 2 milli–arc sec (*24*, *27*). Conversely, a choked

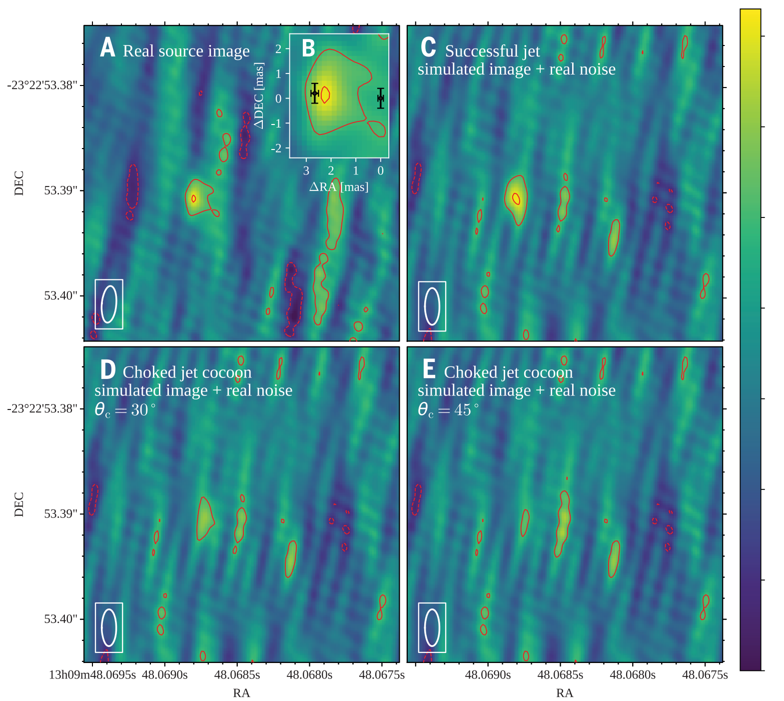

Fig. 1. Observed and simulated radio images of GRB170817A. (**A**) Radio image from our global-VLBI observation (measured brightness root mean square of 8 μJy beam^{-1}). Red contours (dashed for negative values) indicate brightness levels of −20, 20, and 40 μJy beam^{-1}. The beam size (3.5 × 1.5 milli–arc sec) is illustrated by the ellipse in the bottom left. (**B**) A zoom on the position of the source, with black error bars showing previously reported (*23*) centroid positions at 75 days and 230 days after the merger. The source is moving to the left in this orientation. Axes show the projected distance in milli–arc seconds from the position at 75 days. (**C**) Same as (A), but showing a simulated radio image for the structured jet model, convolved to the same beam as the observation, with real noise added. (**D**) Same as (B), but for the choked jet cocoon model with θ_c = 30°. (**E**) Same as (D), but for θ_c = 45°. The structured jet model most closely matches the observations.

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jet cocoon would have a smaller displacement (no detectable displacement and a ring image for a perfectly isotropic outflow) and a larger (>2 milli–arc sec) apparent angular size (Fig. 2). A recent measurement of the displacement of the source apparent position, by 2.67 ± 0.3 milli–arc sec in 155 days (*23*), strongly supports the structured jet scenario. However, those data do not have sufficient resolution to determine the apparent size. We have used global very-long-baseline interferometry (VLBI) observations to place tighter limits on the source angular size, providing an independent constraint on the source structure to that obtained from the apparent motion alone (*23*).

We observed GRB 170817A on 12 to 13 March 2018, 207.4 days after the GW/GRB detection, using 32 radio telescopes spread over five continents. The longest baseline producing useful data was 11,878 km between Hartebeesthoek (South Africa) and Fort Davis (United States). Observations were performed at a central frequency of 4.85 GHz (wavelength of 6.19 cm), with a total bandwidth of 256 MHz. The total on-source time was 7.8 hours (*16*).

The observations showed a source at the sky position right ascension (RA) = $13^h09^m48^s.06880 \pm 0^s.00002$, declination (Dec) = $-23°22'53''.390765 \pm 0''.00025$ [J2000 equinox, 1σ statistical uncertainty (*16*)]. This is within the uncertainty on the position of the optical source (*28*) and compatible with the radio position of the source obtained with the High Sensitivity Array (HSA) (*23*). With respect to the HSA observation at 75 days after the GW event (*23*), our position, measured at 207.4 days, is displaced by δRA(207.4 days – 75 days) = 2.44 ± 0.32 milli–arc secand δDec (207.4 days – 75 days) = 0.14 ± 0.47 milli–arc sec. With respect to the HSA observation at 230 days (*23*), we measured δRA(230 days – 207.4 days) = 0.46 ± 0.34 milli–arc secand δDec(230 days – 207.4 days) = 0.07 ± 0.47 milli–arc sec (1σ statistical uncertainties). Our global VLBI observation, performed shortly after the source flux density peak (Fig. 3), has a position intermediate between those two HSA observations (Fig. 1B) and matches the apparent superluminal motion seen in the HSA data (*23*). We measured a peak brightness of 42 ± 8 microjanskys (μJy) beam^{-1} at 5 GHz. This is consistent with the value 47 ± 9 μJy obtained by interpolating the closest previously published radio observations (*11*, *15*). We also obtained quasi-simultaneous observations with the electronic Multi-Element Radio Linked Interferometer Network (e-MERLIN) array (*16*), measuring a consistent peak brightness upper limit of <60 μJy beam^{-1} (at 3σ significance).

The effective angular resolution of the global VLBI reconstructed image is 1.5 × 3.5 milli–arc sec

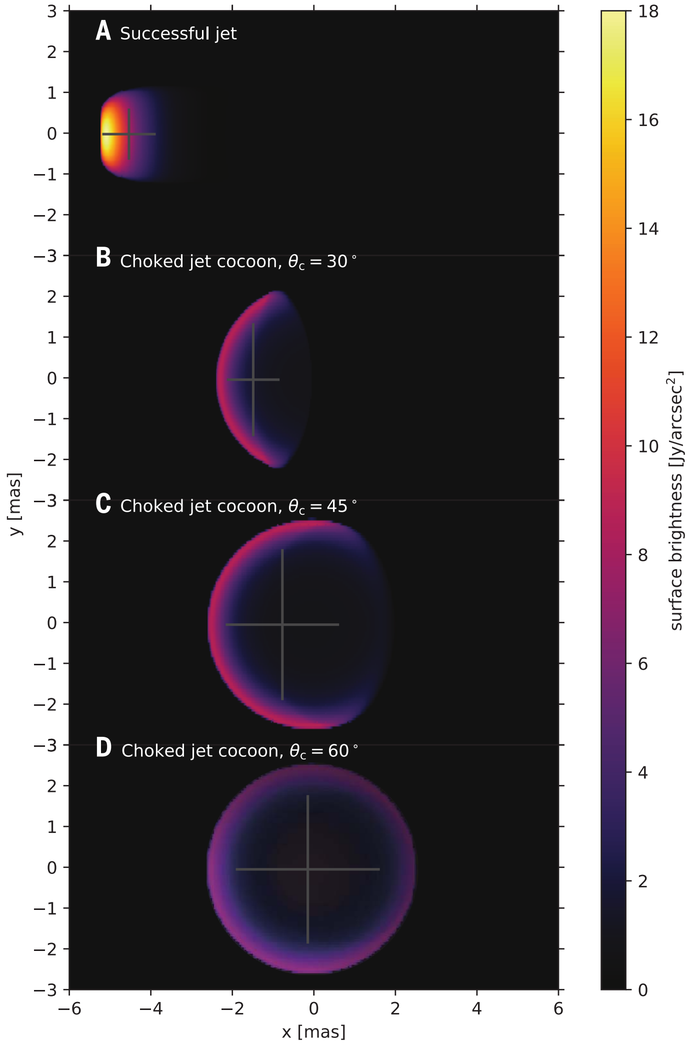

Fig. 2. Predicted source images for our four models. (**A**) Predicted radio brightness distribution at 207.4 days for the structured jet model. (**B** to **D**) Same as (A), but for the choked jet cocoon model with effective opening angles of θ_c = 30° (B), 45° (C), and 60° (D). Gray crosses show the positions and sizes (full widths at half maxima) of elliptical Gaussian fitting of the images. The coordinate origin, in each image, is the projected position of the binary neutron star merger (*16*).

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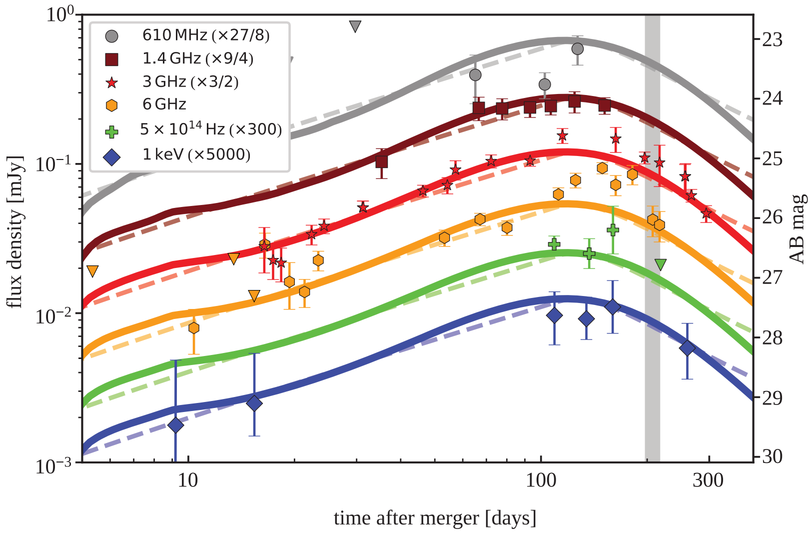

Fig. 3. Multiwavelength light curves of GRB170817. Model curves are shown for the structured jet model (solid lines) and the choked jet cocoon with velocity profile (dashed lines). Models are parametrized as described in (*16*). Upper limits are shown by downward triangles. Data are taken from (*13*, *14*, *15*, *35*), including the optical detection of the afterglow of GRB170817A (*36*). The shaded gray vertical bar marks the date of our global VLBI observation. Data and model curves are shifted by multiplicative factors (given in the legend) for ease of display.

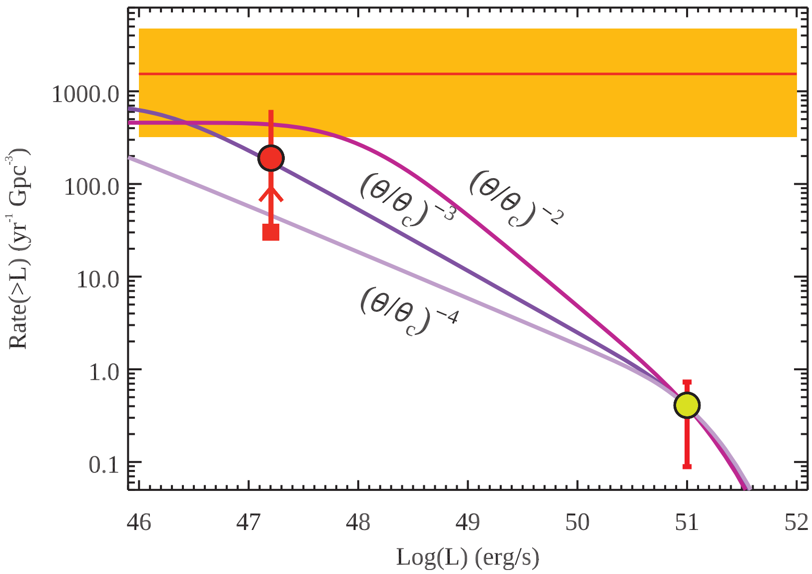

Fig. 4. Short GRB rate as a function of luminosity. The rate of short GRBs with isotropic equivalent luminosity $L_{iso} > 10^{51}$ erg s^{-1} (solid yellow symbol) (*16*) is compared with the expected rate of short GRBs similar to GRB 170817A (solid red symbol (*34*)). We consider this a lower limit: GRB170817A, detected by the Fermi spacecraft, is the only one of its class with an associated GW event, but Fermi could have detected similarly dim events without an associated GW event. Lines show predictions for different jet structures, which are consistent with the estimate based on the detected luminosity of GRB 170817A. The solid red horizontal line shows the rate of binary neutron stars (BNS) mergers inferred from GW data alone (*1*), and the orange shaded region is its 1σ uncertainty.

(*16*). The source in the image appears compact and apparently unresolved with such resolution (Fig. 1A). We calculated (*16*) that the source size at 207 days as measured from the global VLBI image is smaller than 2.5 milli–arc sec at the 90% confidence level (fig. S4).

We compared our data with four possible models of the outflow (*16*), consisting of a successful jet and three variants of the choked jet scenario (Fig. 2). For the successful jet, model parameters were determined from simultaneous fitting [similar to that in (*29*)] of the 3-GHz, optical, and x-ray light curves and of the observed centroid displacement, obtained by comparing the position in our observations to those in the HSA observations (*23*). Adopting jet parameters inferred indirectly from previous observations (*12*, *13*, *19*) yields similar (within 20%) image sizes; thus, our conclusions are not sensitive to the particular parameters chosen. The three choked jet models are characterized by different degrees of anisotropy, parametrized by the outflow collimation angle θ_c ranging from 30° to 60°, all with a viewing angle of 30°. All three choked jet models match the observed multiwavelength light curves. However, their image sizes differ in the three cases and are all larger than the successful jet.

All three choked jet cocoon models are excluded by the image size measured in our observations (*16*). We therefore favor the structured jet model for GRB170817A: a successful jet with a structured angular velocity and energy profile, featuring a narrow ($\theta_c = 3.4 \pm 1°$) and energetic ($E_{iso,core} = E_c = 2.5^{+7.5}_{-2.0} \times 10^{52}$ erg, where $E_{iso,core}$ is the isotropic equivalent energy of the jet core) core seen from a viewing angle of ~15° [a discussion on the uncertainty of the viewing angle is provided in (*16*)]. The synthetic image for this model (Fig. 1C) is similar to the observed image (Fig. 1A). The energy and bulk velocity of the jet material decrease steeply away from the jet axis in our model (*16*), producing a sheath of slower material surrounding the core. The isotropic equivalent luminosity L_{iso} ~ 10^{47} erg s^{-1} of GRB 170817A (*3*, *4*) is lower than that of a typical short GRB. This γ-ray emission was probably not produced by the jet core because its emission would have been too narrowly beamed (because of relativistic effects) to intercept our line of sight. Instead, we infer that the γ-rays were emitted from the part of the sheath moving in our direction; in this case, the slowly rising multiwavelength emission (*10*, *11*, *13*) was due to the subsequent deceleration of parts of the sheath located progressively closer to the jet core. The flattening (*13*) and subsequent peak (*15*) of the light curve (Fig. 3) then mark the time when the emission becomes dominated by the jet core.

If such a jet were observed on-axis, its γ-ray emission would have had an isotropic equivalent luminosity ≥10^{51} erg s^{-1} (assuming 10% efficiency in the conversion of kinetic energy to radiation). Studies of the short GRB (sGRB) luminosity function (*30*, *31*) indicate that the local rate of sGRBs with $L_{iso} > 10^{51}$ erg s^{-1} is ~0.5 year^{-1} Gpc^{-3}. Assuming that all sGRB jets have a similar [quasi-universal (*32*)] structure, and that sGRBs with $L_{iso} > 10^{51}$ erg s^{-1} are produced by jets whose cores point toward Earth, the rate of lower-luminosity events depends on the jet structure owing to the larger number of events visible from larger viewing angles θ_v (*33*). For a structured jet whose luminosity scales as a power law $L(\theta_v) \propto (\theta_v/\theta_c)^{-\alpha}$, as a function of the angular distance θ from the jet axis, the local rate $R_0(>L)$ of events with luminosity larger than L is shown in Fig. 4 for α = 2, 3, 4 (*32*). The rate of GRBs with luminosity as

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low as GRB 170817A (*34*) is consistent with the expected luminosity function of structured jets (Fig. 4). Comparing the resulting rate of jets to the local rate of binary neutron star (NS-NS) mergers, $R_{\mathrm{NS-NS}} = 1540^{+3200}_{-1220}\ \mathrm{year}^{-1}\,\mathrm{Gpc}^{-3}$ as estimated from GW data (*1*), we argue that at least 10% of NS-NS mergers launch a jet that successfully breaks out of the merger ejecta.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S6
Tables S1 and S2
References (*39*–*61*)

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Compact radio emission indicates a structured jet was produced by a binary neutron star merger

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Merging produced a structured jet

The binary neutron star merger event GW170817 was observed with gravitational waves and across the electromagnetic spectrum. However, the physical processes that produced that emission remain poorly understood, particularly the late-time x-ray and radio emission. Ghirlanda *et al.* observed the radio afterglow with an interferometric array of 32 radio telescopes spread across the globe. The size and position of the radio source are not compatible with a uniformly expanding cocoon, as some have suggested. Instead, the data indicate that GW170817 produced a structured jet of material that escaped the surrounding ejecta and is now expanding into the interstellar medium at relativistic speeds.

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