

THE ELECTROMAGNETIC COUNTERPART OF THE BINARY NEUTRON STAR MERGER LIGO/VIRGO GW170817. I. DISCOVERY OF THE OPTICAL COUNTERPART USING THE DARK ENERGY CAMERA

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ABSTRACT

We present the Dark Energy Camera (DECam) discovery of the optical counterpart of the first binary neutron star merger detected through gravitational wave emission, GW170817. Our observations commenced 10.5 hours post-merger, as soon as the localization region became accessible from Chile. We imaged 70 deg² in the i and z bands, covering 93% of the initial integrated localization probability, to a depth necessary to identify likely optical counterparts (e.g., a kilonova). At 11.4 hours post-merger we detected a bright optical transient located 10.6'' from the nucleus of NGC 4993 at redshift $z = 0.0098$, consistent (for $H_0 = 70$ km s⁻¹ Mpc⁻¹) with the distance of 40 ± 8 Mpc reported by the LIGO Scientific Collaboration and the Virgo Collaboration (LVC). At detection the transient had magnitudes $i \approx 17.30$ and $z \approx 17.45$, and thus an absolute magnitude of $M_i = -15.7$, in the luminosity range expected for a kilonova. We identified 1,500 potential transient candidates. Applying simple selection criteria aimed at rejecting background events such as supernovae, we find the transient associated with NGC 4993 as the only remaining plausible counterpart, and reject chance coincidence at the 99.5% confidence level. We therefore conclude that the optical counterpart we have identified near NGC 4993 is associated with GW170817. This discovery ushers in the era of multi-messenger astronomy with gravitational waves, and demonstrates the power of DECam to identify the optical counterparts of gravitational-wave sources.

Keywords: binaries: close — catalogs — gravitational waves — stars: neutron — surveys

1. INTRODUCTION

The joint detection of electromagnetic (EM) and gravitational wave (GW) emission from astrophysical sources is one of the holy grails of present-day astronomy. The primary targets for such joint detections are the mergers of compact object binaries composed of neutron stars (NS) and/or black holes. In such systems the GW emission provides insight into the bulk motions, masses, binary properties, and potentially the composition of neutron stars. Electromagnetic observations provide critical insights into the astrophysics of the event, such as the progenitor environment, the formation of relativistic and non-relativistic outflows, and in some cases the nature of merger products (e.g., Metzger & Berger 2012; Rosswog et al. 2013; Baiotti & Rezzolla 2017). Combining EM and GW observations would lead to deeper scientific insights into some of the most cataclysmic events in the Universe. These multi-messenger observations also allow for novel measurements, such as standard siren measurements of the Hubble constant (Schutz 1986a; Holz & Hughes 2005; Dalal et al. 2006; Nissanke et al. 2010, 2013), and studies of gamma-ray bursts (Berger 2014).

A wide range of EM emission mechanisms for GW sources have been proposed over the years (Metzger & Berger 2012), including short-duration GRBs (Eichler et al. 1989; Nakar 2007; Berger 2014), on- or off-axis afterglow emission from radio to X-rays (van Eerten & MacFadyen 2011; Coward et al. 2014; Fong et al. 2015; Lamb & Kobayashi 2016), optical/near-IR emission due to radioactive decay of r -process nuclei synthesized in the merger ejecta (so-called kilonova; Li & Paczyński 1998; Rosswog et al. 1999; Metzger et al. 2010; Barnes & Kasen 2013), and radio emission produced by interaction of the kilonova ejecta with the circumbinary medium (Nakar & Piran 2011; Metzger & Berger 2012).

The search for optical counterparts is particularly attractive due to the combination of emission that, unlike GRB emission, is not highly beamed and wide-field optical telescope facilities; a detection can then be followed up at other wavelengths with narrow-field instruments. Over the last two years, we have used the Dark Energy Camera (DECam, Flaugher et al. 2015), a 3 deg² wide-field imager on the Blanco 4-m telescope at the Cerro Tololo Inter-American Observatory (CTIO), to follow up GW sources from Advanced LIGO (Abbott et al. 2009) and Virgo (Acernese et al. 2015) detectors (see, e.g., Abbott et al. 2016b; Dark Energy Survey Collaboration et al. 2016). In particular, we conducted rapid follow-up observations of the black hole binary merger events GW150914 (Abbott et al. 2016c) and GW151226

(Abbott et al. 2016a), using DECam (Soares-Santos et al. 2016; Annis et al. 2016; Cowperthwaite et al. 2016). No optical counterpart was discovered in either case.

On 2017 August 17 at 12:41:06 UT the Advanced LIGO/Virgo (ALV) observatories detected a binary neutron star merger, GW170817 (LIGO Scientific Collaboration and Virgo Collaboration 2017b,d,a). At 23:12:59 UT (10.53 hours after the GW detection) we began to image a 70.4 deg² region that covered 93% of the localization probability in the map provided by the LVC at the time (LIGO Scientific Collaboration and Virgo Collaboration 2017c). Immediately following the identification by one of us (R. Chornock), we received a private communication from another DECam team member (R. Foley) indicating that the source was also discovered in an image taken 0.5 hours ahead of ours by the Swope Telescope. We issued a circular to the Gamma-ray Coordination Network (GCN) reporting the discovery at 01:15:01UT (Allam et al. 2017), including a reference to a GCN from the 1M2H collaboration at 01:05:23 UT (SSS17a; Coutler et al. 2017), and subsequent to our GCN the DLT40 team also announced an independent detection (DLT17ck; Yang et al. 2017 reported at 01:41:13 UT); see (LIGO Scientific Collaboration and Virgo Collaboration, et al. 2017a) for an overview of the observations carried out by the community. This transient has received an International Astronomical Union name of AT2017gfo.

Subsequent to our discovery of the optical transient, we obtained follow-up observations with a wide range of telescopes, spanning radio to X-rays, which are detailed in the associated papers of this series: Cowperthwaite et al. (2017); Nicholl et al. (2017); Chornock et al. (2017); Margutti et al. (2017); Alexander et al. (2017); Blanchard et al. (2017); Fong et al. (2017).

Here, in the first paper of the series, we present our DECam observations, the discovery of the optical transient, and a search for other potential counterparts across the 70.4 deg² region. We find no other potential optical counterpart within the GW localization region, thus helping to significantly establish the association between the detected optical transient and GW170817. A measurement of the Hubble constant, the first utilizing a gravitational wave event as a standard siren measurement of distance (Schutz 1986b; Dalal et al. 2006), is enabled by this work and is described in LIGO Scientific Collaboration and Virgo Collaboration, et al. (2017b).

2. DECam COUNTERPART SEARCH

The alert for GW170817 was issued 40 minutes after the trigger, on 2017 August 17 at 13:21 UT (LIGO Scientific Collaboration and Virgo Collaboration 2017b), and

was promptly received by our automated GCN listener system. Two subsequent GCN circulars indicated that the high-significance candidate was consistent with a binary neutron star merger at $d \approx 40$ Mpc and coincident within 2 seconds with a short burst of gamma-rays detected by Fermi GBM (LIGO Scientific Collaboration and Virgo Collaboration 2017b,d). Four hours later a sky localization map obtained from the three-detector ALV network was provided (LIGO Scientific Collaboration and Virgo Collaboration 2017c).

The entire GW localization region was visible from Chile at the beginning of the night, setting within the first ~ 1.5 hours. Our DECam observations commenced at 23:13 UT (10.53 hours post merger) with 30 sec exposures in i - and z -band. The resulting 5σ limiting magnitudes are $i \approx 22.0$ and $z \approx 21.3$ for point sources. The pre-determined sequence of observations consisted of 18 pointings (hexes), each with a 3 deg^2 coverage, with a second offset sequence to mitigate loss of area (e.g., due to gaps between CCDs). The resulting areal coverage was 70.4 deg^2 , corresponding to an integrated probability of 93.4% of the initial GW sky map. Additional details of the pointing and sequencing determination algorithm are available in Herner et al. (2017). While our sequence of observations was on-going, a new localization map was released at 23:54 UT (LIGO Scientific Collaboration and Virgo Collaboration 2017e). While the overall shape of the two maps are similar, the probability peak was shifted significantly. In the revised map the integrated probability of our observations is 80.7%.

2.1. Discovery and Observations

We performed a visual inspection of raw, unprocessed DECam images to find new point sources near relatively bright galaxies in comparison to archival Pan-STARRS1 3π survey images (Chambers et al. 2016). This process resulted in the discovery of a new source near the galaxy NGC 4993 (see Figure 1). The galaxy is located at $z = 0.0098$ which is, for a value of H_0 of 70 km/s/Mpc, consistent with the 40 ± 8 Mpc reported by the LVC in their GCN for GW170817. The transient is located at coordinates RA, Dec = 197.450374, -23.381495 (13h09m48.09s -23d22m53.38s) between the 50% and 90% contours in both the initial and shifted maps (see Figure 2).

At the time when the galaxy was imaged (11.40 hours post-merger) the optical transient had magnitudes of $i = 17.30 \pm 0.01$ and $z = 17.43 \pm 0.01$. We continued to observe the optical counterpart with DECam nightly in the $ugrizY$ filters until it became undetectable (at limiting magnitude ~ 22.5 mag) in each band and the source location became inaccessible to the telescope. Our last deep image of the source is on 2017 August 31, 14.5 days post-merger. These follow-up observations are discussed in detail in Cowperthwaite et al. (2017).

We process all images with the DES single-epoch processing (Drlica-Wagner et al. 2017; Morganson et al. 2017, and references there in) and difference imaging (diffimg) pipelines (Kessler et al. 2015). The diffimg software works by comparing search images and one or more reference images (templates) obtained before or after the search images. We use our own imaging plus publicly available DECam data from the NOAO Science Archive (portal-noao.noao.edu) as templates, requiring exposures of at least 30 sec. At the position of the counterpart, pre-existing templates were available in g, r bands. For u, i, z, Y images we used exposures taken after the source had faded (u : 25 August 2017; i, z, Y : 31 August 2017).

The photometric results from diffimg are shown in Figure 3 and Table 1. The diffimg pipeline uses the well tested DES calibration module expCalib. The $ugrizY$ photometry presented in Table 1 has calibration errors relative to DES photometry of $\lesssim 2\%$. We implemented a galaxy morphological fit and subtraction method, making use of a fast multi-component fitting software (Imfit, Erwin 2015) followed by PSF photometry and a Pan-STARRS PS1 calibration to double check the reduction. Results agree within uncertainties and calibration differences. The photometry used in the next paper in this series, (Cowperthwaite et al. 2017), measured using a difference image reduction using Pan-STARRS PS1 templates, also agrees within uncertainties.

Table 1. Light curve constructed from u, g, r, i, z, Y observations. Columns are observation time, band, magnitude and its errors. Magnitudes are galactic extinction corrected AB PSF magnitudes.

MJD	Band	Mag ¹	σ_m
57983.00306	i	17.27	0.005
57983.00374	z	17.42	0.007
57983.97395	Y	17.27	0.008

¹ $E(B-V)_{SFD98} = 0.123$, and $R_V = 3.963, 3.186, 2.140, 1.569, 1.1048$ for u, g, r, i, z, Y bands, respectively.

NOTE—Full table available as machine-readable in the online version. A portion is shown here for guidance regarding its form and content.

3. WIDE AREA SEARCH

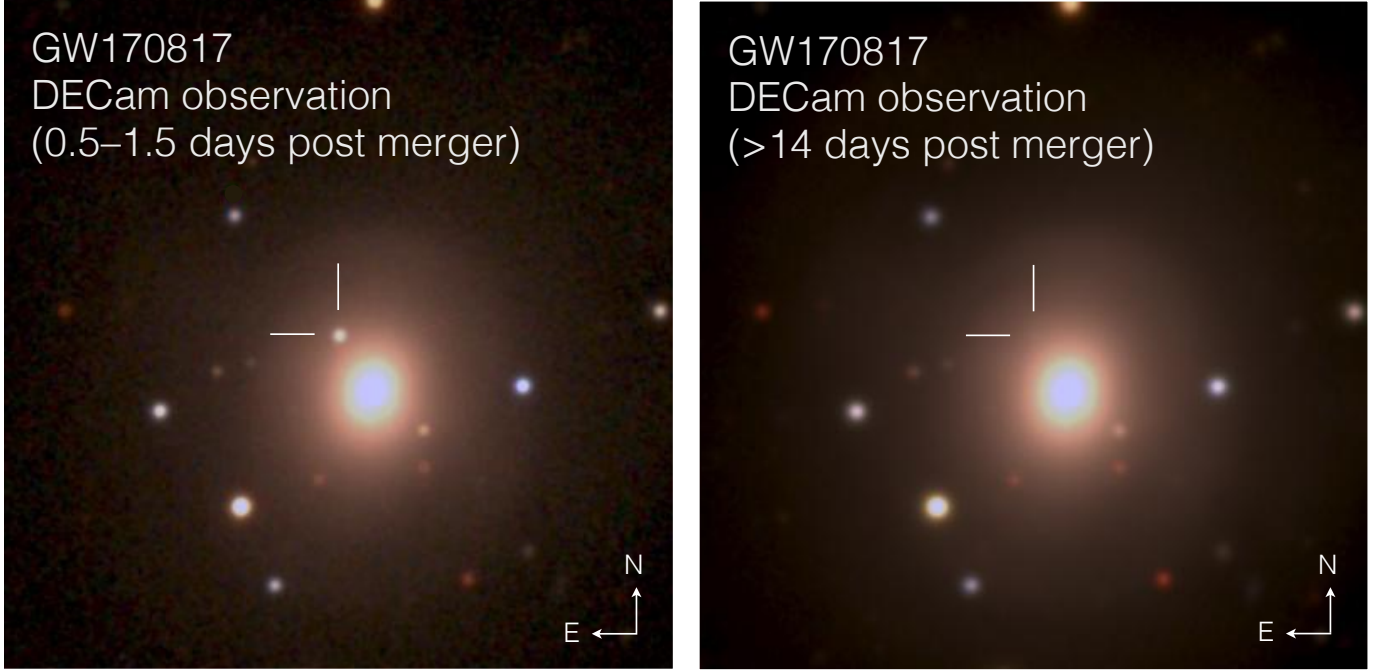


Figure 1. NGC4993 *grz* color composites ($1.5' \times 1.5'$). Left: Composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the *g* and *r* images taken 1 day later; the optical counterpart of GW170817 is at RA,Dec = 197.450374, -23.381495 . Right: The same area two weeks later.

Our primary program is to obtain images over the LIGO probability map to search for counterparts. Within 12 hours of the event we had obtained DECam *i*, *z* images across $> 80\%$ of the revised LIGO probability map. We have analyzed this region to determine how many potential counterparts are present.

3.1. Image Processing

We employ the DES single-epoch processing and `diffimg` pipelines to produce a list of transient candidates. The search images are 72 exposures taken on the night of the trigger (corresponding to two tilings of 18 hexes in *i* and *z* bands). Because most of the exposures ($\sim 60\%$) did not have pre-existing DECam imaging in those bands, we took images on the nights of 31 August through 2 September to serve as templates. We expect any kilonova-like transients to have faded below detection thresholds by that time (~ 2 weeks from the trigger).

The total area encompassed by the 72 exposures is 70.4 deg^2 . The camera fill factor is 80% which results in 4% area loss when we consider the two overlapping tilings. Weather on the nights of template observations was partially clouded and caused a 3% loss. Processing failures accounted for less than 1% loss. The final area included in this search for other potential counterparts is 64.6 square degrees.

This process results in 1500 transient candidates with magnitudes between 15.5 and 20.5. A candidate is defined as a detection meeting `diffimg` quality requirements (see Table 3 of Kessler et al. (2015)) on at least two search exposures.

The magnitude cutoff of this analysis is limited by the depth of the template images: $i = 21.2$ and $z = 20.5$, to be compared with the depth of the search images: $i = 22.0$ and $z = 21.3$.

3.2. Candidate Selection

We apply several selection criteria to candidates identified in `diffimg` aiming to reject moving objects, background artifacts and long-lived transients:

- Criterion 1: The candidate must have at least one detection in *i* and one detection in *z* band.
- Criterion 2: The candidate must pass our automated scanning program (Goldstein et al. 2015) with a machine learning score ≥ 0.7 in all detections. This criterion rejects non-astrophysical artifacts. The efficiency of this criterion as measured from point sources injected into our images is $\approx 90 - 100\%$ for both *i* and $z \approx 17 - 22$ mag.
- Criterion 3: The candidate must have faded significantly between the search (first) and template (last) observations. Specifically, we require the change in the candidate flux to be greater, at 3σ level, than the flux in a circular aperture of radius = 5 pixels on the template image. This criterion eliminates slow-evolving transients (e.g., supernovae).

Table 2 lists the number of events passing each selection stage in various bins of magnitude. After all criteria are ap-

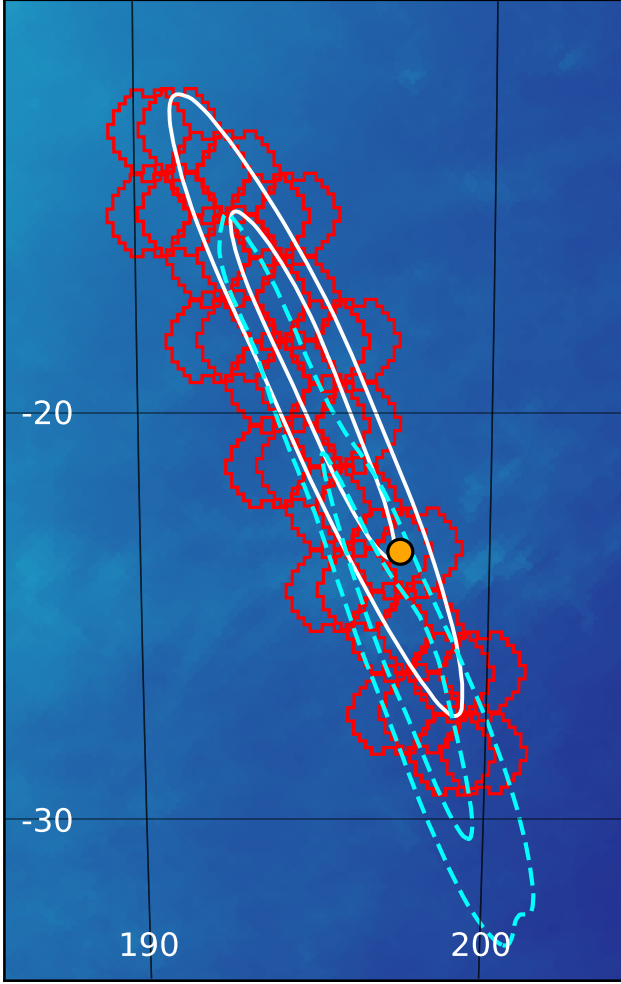


Figure 2. Location of the optical counterpart of GW170817 on the probability maps provided by the LVC (white solid: initial; cyan dashed: revised; inner and outer contours show 50% and 90% probability respectively) and relative to our search area (red: DECAM sky footprint).

plied, one optical counterpart candidate remains: the source discovered by visual inspection. Slow moving solar system objects, which could potentially have met the selection criteria above, are very rare in the magnitude range of this search. The flares of M dwarf flare stars have $T \approx 10,000$ K and therefore are very blue; they are rejected by selection criterion 3 in z -band.

4. UNIQUENESS OF THE CANDIDATE

This analysis shows that the source we discovered is the only one plausibly associated with the GW event within the region searched. To estimate its significance we compute the chance probability of a transient to occur within the volume and timescale of interest. Because SNe are by far the most likely transient contaminant, we use their rate and timescale to make a conservative estimate. We use a combined rate of

Table 2. Number of candidates at each selection stage, sorted by i -band magnitude.

mag(i)	Raw	Cut 1	Cut 2	Cut 3
15.5–16.5	4	0	0	0
16.5–17.5	11	7	3	1
17.5–18.5	26	15	7	0
18.5–19.5	296	63	27	0
19.5–20.5	1163	167	44	0
Total	1500	252	81	1

$1 \times 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1}$, for core-collapse (Strolger et al. 2015) and Type Ia (Dilday et al. 2008) SNe at $z \lesssim 0.1$. The characteristic timescale of SNe is $\tau \sim 1$ month. The volume (V) we observed is estimated as a shell at $z \sim 0.01$ (~ 40 Mpc) spanning 64 deg^2 area and 16 Mpc width corresponding to the effective search area and the distance uncertainty, respectively: $V = 558 \text{ Mpc}^3$. Under these assumptions, we find that the probability of a chance coincidence is $\sim 0.5\%$, and we conclude that our optical transient is associated with GW170817.

5. CONCLUSION

We report the DECAM discovery of the optical counterpart to the BNS merger GW170817, an object with $i = 17.30$ mag and $z = 17.43$ mag at 11.40 hours post-merger. The source was discovered through visual inspection of nearby galaxies in our raw data stream. Our analysis identifies this source as the only credible optical counterpart within a large fraction of the GW170817 sky map. The observed peak absolute magnitude of $M_i = -15.7$ is about 1000 times brighter than a nova, which is typically close to Eddington luminosity ($M_V = -9$). Thus, we have indeed discovered a kilonova as the name defines it and was predicted in Metzger et al. (2010).

At $M_i = -15.7$, the optical transient is bright enough for us to detect it out to 425 Mpc. Its properties, 1.5 days after the event include: $(i - z) = 0.2$, and a magnitude decline versus time in $i, z, Y \propto t^{-\frac{1}{2}}$, and faster decline in g -band ($\propto t^{-\frac{3}{2}}$). Future searches for counterparts of GW events may be improved by this information.

This detection has opened a new era of multi-probe multi-messenger astronomical observations of the Universe that will bring new measurements of cosmological parameters, starting with the present rate of expansion (LIGO Scientific Collaboration and Virgo Collaboration, et al. 2017b), and possibly helping determine the matter/energy content and evolution of the Universe.

This is the first detection of an optical counterpart of a gravitational wave source. It will not be the last. As the LIGO

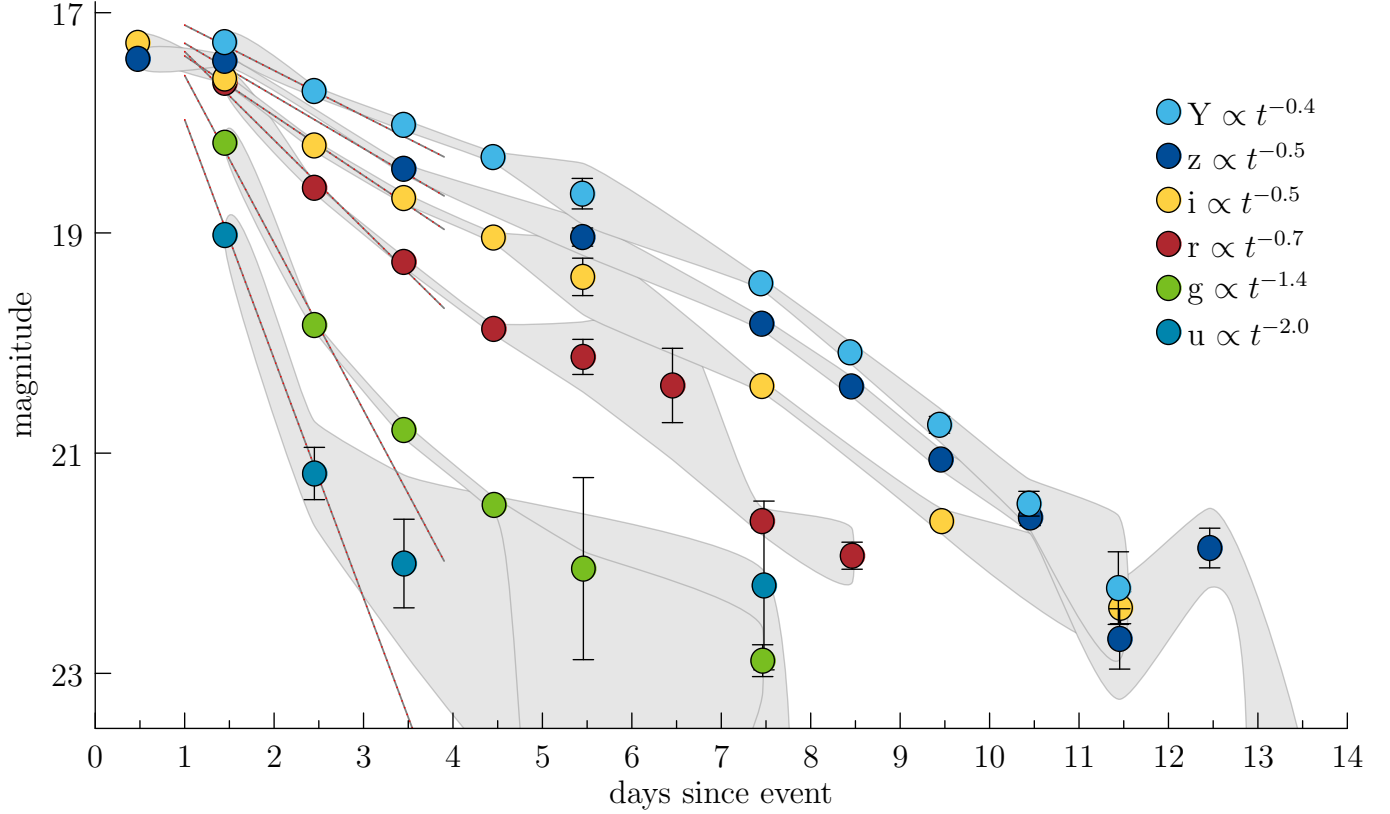


Figure 3. The observed light curve for the optical counterpart of GW170817 measured in 6 filters. The data points and 1σ error bars were measured using `diffimg`. The gray bands represent the 95% confidence interval about each measurement, or 2σ above sky if the measured flux is less than $2\sigma_{\text{sky}}$. Data taken on days 5.5, 6.5 and 11.5 were obtained in poor weather conditions, hence the broader uncertainty bands. The photometry has been checked against a difference imaging reduction using Pan-STARRS PS1 templates (Cowperthwaite et al. 2017) and a galaxy fit & subtract PSF source magnitude reduction; these measurements are consistent with our results. The dashed lines show the initial decay of the source: $m \propto t^{-\alpha}$, where $\alpha = (2.0, 1.4, 0.7, 0.5, 0.5, 0.4)$ in u,g,r,i,z,Y bands respectively. The decay in the first few days is consistent with a peak luminosity near $t = 1$ day. The table containing light curve information is available as a machine-readable file (Table 1).

and Virgo collaborations proceed to their next observing runs and upgrades, DECam will continue to play an important, almost unique, role in the identification of gravitational wave sources in the Southern hemisphere.

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