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The Discovery of the Electromagnetic Counterpart of GW170817: Kilonova AT 2017gfo/DLT17ck

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Abstract

During the second observing run of the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo Interferometer, a gravitational-wave signal consistent with a binary neutron star coalescence was detected on 2017 August 17th (GW170817), quickly followed by a coincident short gamma-ray burst trigger detected by the *Fermi* satellite. The Distance Less Than 40 (DLT40) Mpc supernova search performed pointed follow-up observations of a sample of galaxies regularly monitored by the survey that fell within the combined LIGO+Virgo localization region and the larger *Fermi* gamma-ray burst error box. Here we report the discovery of a new optical transient (DLT17ck, also known as SSS17a; it has also been registered as AT 2017gfo) spatially and temporally coincident with GW170817. The photometric and spectroscopic evolution of DLT17ck is unique, with an absolute peak magnitude of $M_r = -15.8 \pm 0.1$ and an r-band decline rate of 1.1 mag day^{-1}. This fast evolution is generically consistent with kilonova models, which have been predicted as the optical counterpart to binary neutron star coalescences. Analysis of archival DLT40 data does not show any sign of transient activity at the location of DLT17ck down to $r \sim 19$ mag in the time period between 8 months and 21 days prior to GW170817. This discovery represents the beginning of a new era for multi-messenger astronomy, opening a new path by which to study and understand binary neutron star coalescences, short gamma-ray bursts, and their optical counterparts.

Key words: stars: neutron – surveys

1. Introduction

The era of multi-messenger astronomy has truly begun. During the first advanced LIGO (aLIGO; Aasi et al. 2015) run (O1), two definitive gravitational-wave (GW) events were observed, corresponding to relatively massive black hole–black hole (BH–BH) mergers of 36 + 25 $M_\odot$ (GW150914; Abbott et al. 2016d) and 14 + 8 $M_\odot$ (GW151226; Abbott et al. 2016c), respectively. These amazing discoveries were followed by a third event during the second aLIGO run (O2), which was another massive BH–BH merger of 31 + 19 $M_\odot$ (Abbott et al. 2017). Each GW event was accompanied by a massive effort from the astronomical community to identify an electromagnetic (EM) counterpart (see e.g., Abbott et al. 2016b), even though the likelihood of finding EM counterparts to BH–BH mergers is low. On the other hand, GW events including at least one neutron star (NS; as either an NS–NS or NS–BH coalescence) are expected to produce a variety of EM signatures. Chief among them in the optical+near-infrared regime is the so-called kilonova, resulting from the decay of r-process elements produced and ejected during the merger process (for a review, see Metzger 2017).

In order to search for kilonovae, two general approaches have been proposed: (1) wide-field searches of the aLIGO localization region (e.g., Smartt et al. 2016) and (2) narrow-field targeted searches of galaxies both at the predicted GW event distance and within the sky localization region (e.g., Gehrels et al. 2016). The Distance Less Than 40 (DLT40) Mpc one-day cadence supernova search uses the second approach, targeting galaxies within the GW localization region that are part of the main supernova search.

On 2017 August 17 (UT) a GW event was discovered by aLIGO and Virgo (Acernese et al. 2015) observatories (LIGO-Virgo collaboration, hereafter LVC) that was consistent with a neutron star binary coalescence with a low false alarm rate, at a distance of $D \sim 40$ Mpc (Connaughton & GBM-LIGO Group 2017; see Section 3 for further details). A potential short gamma-ray burst (GRB) counterpart was discovered by *Fermi* (GBM; trigger 524666471). Soon after, multiple groups reported the detection of an optical counterpart (AT 2017gfo/DLT17ck/SSS17a; we will refer to the counterpart as DLT17ck throughout this work), which was subsequently identified as a true kilonova based on its fast spectroscopic (Lyman et al. 2017) and photometric (Yang et al. 2017a) evolution. The apparent host galaxy of DLT17ck is the normal early-type galaxy NGC 4993 (see Sadler et al. 2017).

In this paper we present the observations of the DLT40 team associated with the kilonova DLT17ck, based on our ongoing one-day cadence search. The DLT40 team was one of the initial groups reporting the discovery of the kilonova (Section 3), and based on our light curve and an early spectrum, we show that DLT17ck resembles the expected observables of a kilonova (Section 4). The DLT40 team also has a history of observations of the NGC 4993 field during the year before the GW event (Section 5). We end the paper by summarizing our results, and discussing prospects for EM counterpart searches with small telescopes (Section 6).

2. DLT40 GW Counterpart Search

The DLT40 Mpc survey (L. Tartaglia et al. 2017, in preparation) is a one-day cadence supernova search using a PROMPT 0.4 m telescope located at Cerro Tololo Inter-American Observatory (Reichart et al. 2005). The survey goal is the early detection and characterization of nearby supernovae (SNe). DLT40 has been operational since 2016, and observes ∼300–600 targeted galaxies on a nightly basis. A typical single-epoch integration of 45 s reaches a limiting magnitude of $r \approx 19$ mag with filterless observations. The field of view of the PROMPT camera is 10×10 arcmin^2, sufficient to map all but the nearest galaxies in the search.

The DLT40 galaxy sample is drawn from the Gravitational Wave Galaxy Catalog (White et al. 2011), with further cuts made on recessional velocity ($V > 3000$ km s^{-1}, corresponding to $D \lesssim 40$ Mpc), declination (Dec $> +20$ deg), absolute magnitude ($M_B > -18$ mag), and Milky Way extinction ($A_V > 0.5$ mag). For these galaxies, we strive for a one-day cadence between observations to constrain the explosion epoch of any potential SN.

The DLT40 pipeline is totally automated, with pre-reduced images delivered from the telescope, ingested, and processed in a few minutes. New transient candidates are detected on difference images and are available for visual inspection within ∼2–3 minutes of ingestion. At the time of writing, DLT40 has discovered and confirmed 12 young SNe in the nearby Universe, with initial results reported in Hosseinzadeh et al. (2017).

The DLT40 GW follow-up strategy was planned as a straightforward addition to the core DLT40 supernova search. When a LVC GW event is announced, the BAYESTAR sky map (Singer & Price 2016) is cross-matched with the DLT40 galaxy sample. All DLT40 galaxies that are within the LVC localization area are selected for high-priority imaging in the nightly DLT40 schedule. Depending on the size of the LVC localization area and the number of galaxies selected, we apply a spatial cut (between the 80%–99% confidence localization contours of the LVC map) and/or a cut in luminosity to select the galaxies with the greatest stellar mass. This strategy broadly follows that laid out by other LVC EM follow-up groups with narrow-field telescopes (e.g., Gehrels et al. 2016). Further details of our search strategy, and our other results from O2, will be presented in a separate work (S. Yang et al. 2017, in preparation).

3. Discovery of DLT17ck

On 2017 August 17.528 UT, the LVC reported the detection of a GW nearly coincident in time (2 s before, Connaughton & GBM-LIGO Group 2017) with the *Fermi* GBM trigger 524666471/170817529 located at R.A. $= 176{\overset{\circ}{.}}8$ and decl. $= -39{\overset{\circ}{.}}8$, with an error of $11{\overset{\circ}{.}}6$ (at 1σ). The LVC candidate had an initial localization of R.A. $= 186{\overset{\circ}{.}}62$, decl. $= -48{\overset{\circ}{.}}84$, with a 1σ error radius of $17{\overset{\circ}{.}}45$ (LIGO Scientific Collaboration & Virgo Collaboration 2017a). The GW candidate was consistent with a neutron star binary coalescence with a false alarm rate of ∼1/10,000 years (LIGO Scientific Collaboration & Virgo Collaboration 2017a). The GW was clearly detected in the LIGO detectors but was below threshold for the Virgo detector (LIGO Scientific Collaboration & Virgo Collaboration 2017b). Despite this, the Virgo data were still crucial in order to further constrain the localization of the event to only 31 deg^2 (90% credible region). The luminosity distance was constrained with LIGO data to be 40 ± 8 Mpc (LIGO Scientific Collaboration & Virgo Collaboration 2017b). In Figure 1 we show a map of both the LIGO+Virgo and *Fermi* GBM localizations, which overlapped on the sky. As part of the DLT40 search, we prioritized observations of 20 galaxies within the 99% confidence area of the LVC error box and with a cut in luminosity. Among the 23 galaxies within the LIGO/Virgo error box, we selected the 20 galaxies within 99% of the cumulative luminosity distribution. At the same time, we also selected the 31 most luminous galaxies in the *Fermi* region of the coincident short GRB (see Figure 1). The 51 DLT40 galaxies selected were then observed at high priority. In this work, we present the only transient we detected within either the LVC or *Fermi* localizations: AT 2017gfo/DLT17ck (detected in in NGC 4993).

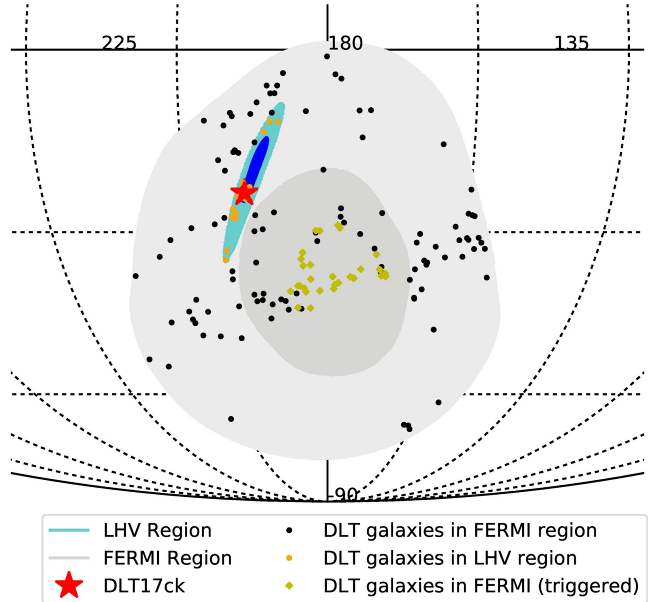

Figure 1. Sky map region of the GW170817 LVC event using all three gravitational-wave observatories (H1, L1, and V1) over-imposed on the *Fermi* localization of GBM trigger 524666471/170817529. The DLT40 galaxies observed the first Chilean night after the LVC trigger are marked in orange (galaxies within the LVC region) and in olive green (galaxies within the *Fermi* localization). The remaining black points are those DLT40 galaxies which were within the *Fermi* localization but were not observed by our program. The red star marks the location of DLT17ck and the host galaxy NGC 4993.

On 2017 August 17 23:49:55 UT (11.09 hr after the LVC event GW170817), we detected DLT17ck, at R.A. = 13:09:48.09 and decl. = −23:22:53.4.6, 5.37W, 8.60S arcsec offset from the center of NGC 4993 (Yang et al. 2017b, see Figure 2). At the same time, DLT17ck was detected by Coulter et al. (2017), Allam et al. (2017), Melandri et al. (2017), and Arcavi et al. (2017) and intensively observed by portions of the astronomical community that signed a memorandum of understanding with the LVC. DLT17ck was not reported to the internal (collaboration-wide) GCN by our team until a second confirmation image was obtained on August 18 00:40:38 UT. The LVC GW region of GW170817 was also observed in other windows of the EM spectrum, from radio to X-ray wavelengths. It was recovered in the UV, optical, and near-infrared. Deep X-ray follow-up observations conducted with the *Chandra* observatory revealed X-ray emission from a point source at a position consistent with that of the optical transient DLT17ck (Bartos et al. 2017b; Fong

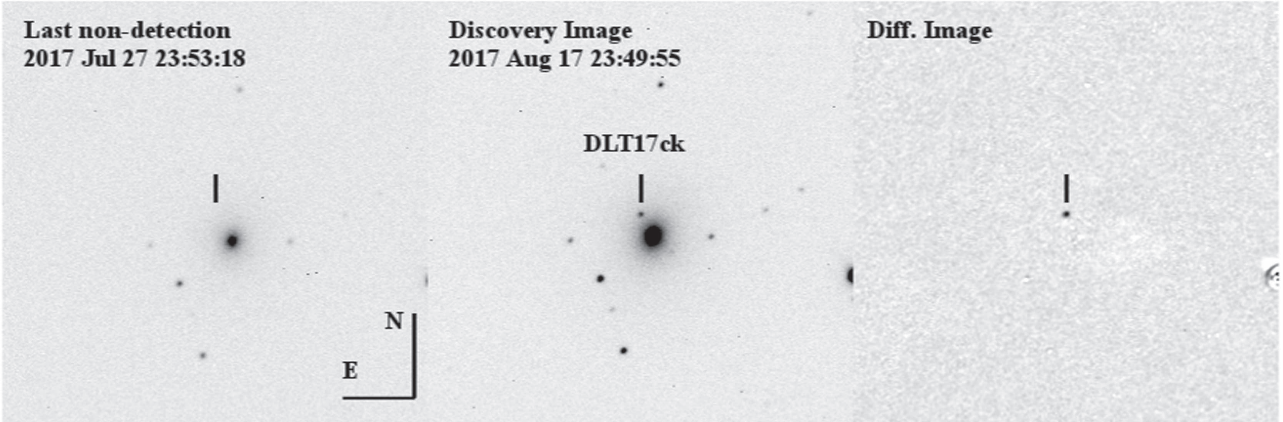

Figure 2. Last non-detection (on the left) discovery image of DLT17ck observed on 2017 August 17 at 23:49:55 UT. The difference image is shown on the right, where DLT17ck is clearly visible.

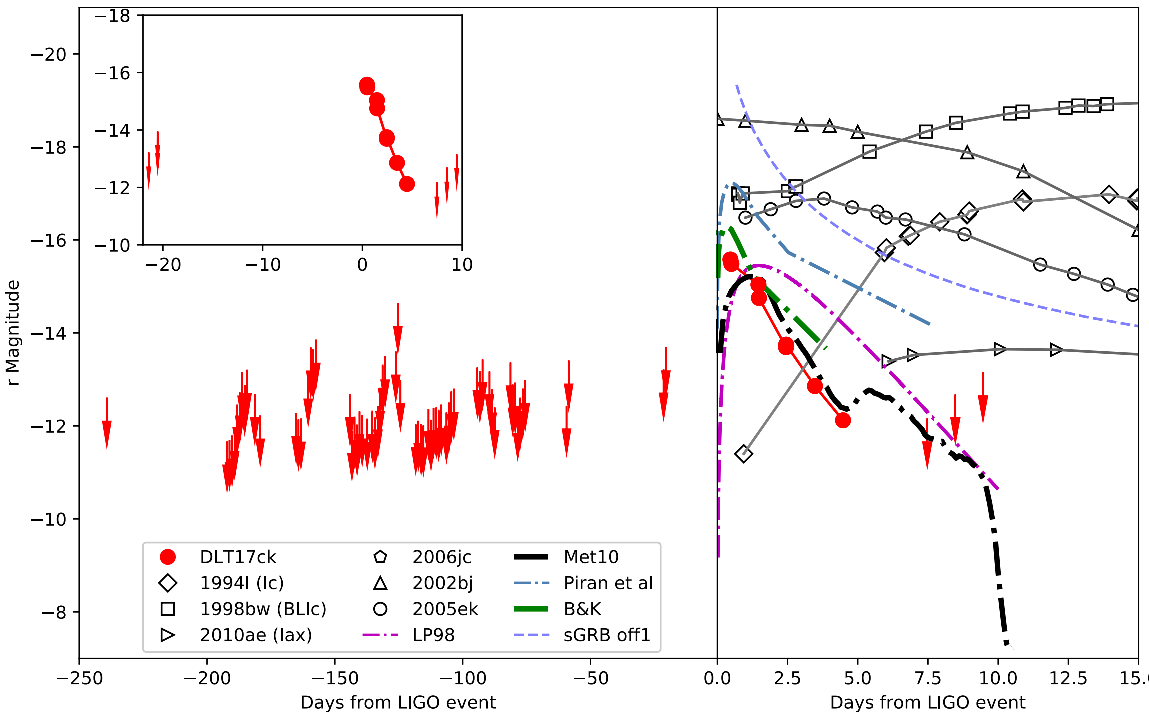

Figure 3. Right panel: DLT40 light curve of DLT17ck (in red) over-plotted with normal or fast-evolving SNe (in gray). Several NS–NS merger models, scaled to a distance of 40 Mpc, are shown for comparison from Li & Paczyński (1998; LP98); Metzger et al. (2010; Met10); Barnes & Kasen (2013; B&K), and Piran et al. (2013; Piran et al). Left panel: we show the detection limits in the position of DLT17ck in the six months before GW170817 and an inset with the detected light curve.

et al. 2017; Troja et al. 2017). A radio source consistent with the position of DLT17ck (Adams et al. 2017) was detected with the Karl G. Jansky VLA (Mooley et al. 2017; Corsi et al. 2017) at two different frequencies (≈3 GHz and ≈6 GHz). Marginal evidence for radio excess emission at the location of DLT17ck was also found in ATCA images of the field at similar radio frequencies (≈5 GHz; Bartos et al. 2017b). Finally, neutrino observations were reported with one neutrino detected within the preliminary LVC localization (Bartos et al. 2017a), though this was later established to be unrelated to GW170817/DLT17ck (Bartos et al. 2017b).

4. DLT17ck: A New Type of Transient

Our discovery magnitude $r = 17.46 \pm 0.03$ mag at the distance of 39.5 ± 2.6 Mpc (distance modulus, $\mu = 32.98 \pm 0.15$ mag using the Tully–Fisher relation; Freedman et al. 2001) and Milky Way reddening $E(B - V) = 0.109$ mag (Schlafly & Finkbeiner 2011) brings DLT17ck to an absolute magnitude of $M_r = -15.8 \pm 0.1$ mag. This magnitude is consistent with that typically observed in faint core-collapse SNe (Spiro et al. 2014) and brighter than that of some kilonova models proposed so far. However, in the hours after the discovery, it became clear that DLT17ck was a unique event. DLT17ck was indeed cooling down and getting dimmer much faster than any other SN we had ever observed. About 35 hr after GW170817, DLT17ck had dimmed by almost a magnitude (Yang et al. 2017a). By day five, DLT17ck was already ∼4 mag fainter than at discovery and disappeared below our magnitude limit the day after. At the same time, DLT17ck remained detectable in the near-infrared for a longer time. In Figure 3 (right panel), we compare the DLT40 light curve of DLT17ck with those of the most rapid transients available in the literature. DLT17ck evolves faster than any other known SN (gray points) and peaked probably between our discovery images and our third detection (11 and 35 hr after GW170817, respectively).[7]

Regardless of the energy source powering them, the light curves of astronomical transients like supernovae and kilonovae are regulated by the same physics. At early times, the photons released cannot immediately escape due to the high optical depth. The photon *diffusion time* depends on the ejecta mass, the opacity, and the ejecta velocity (Arnett 1982). For kilonovae, the ejected mass has been predicted to be between 10^{-4} and $10^{-2}\,M_{\odot}$, depending on the lifetime of the hypermassive NS that forms at the moment of coalescence. A longer lifetime corresponds to a larger ejected mass and a brighter and longer-lasting optical EM counterpart (Kasen et al. 2013; Metzger 2017).

Because of the high neutron fraction, the nucleosynthesis in the ejected material is driven by the r-process, producing a significant fraction of lanthanide that dominates the opacity. Because of a large uncertainty in lanthanide opacity, the ejecta opacity is not well constrained; it should be between 1 and $100\,\mathrm{cm^2\,g^{-1}}$ (closer to 1 for ejecta with a small amount of lanthanide elements; Metzger 2017). Finally, velocities in the range 0.1–0.3 times the speed of light are also expected (see Metzger 2017, and reference therein). Using Equation (5) from Metzger (2017),

$$t_{\mathrm{peak}} \equiv \left(\frac{3Mk}{4\pi\beta vc}\right)^{1/2} \approx 1.6d\left(\frac{M}{10^{-2}\,M_{\odot}}\right)^{1/2}\left(\frac{v}{0.1c}\right)^{-1/2} \times \left(\frac{k}{1\mathrm{cm^2\,g^{-1}}}\right)^{1/2} \quad (1)$$

where $\beta \approx 3$, M is the ejected mass, v is the expansion velocity, k the opacity, and t_{peak} is the time of the peak, we can give a a rough estimate of the ejected mass. Soon after our first detection (11 hr after explosion), a few groups reported a flattening or slight increase of the luminosity (Wolf et al. 2017; Arcavi et al. 2017), but our second detection (35 hr after explosion) shows the object fading. We then assume August 18.528 UT (24 hr after GW170817) as the epoch of the peak. We use an opacity of 1–$10\,\mathrm{cm^2\,g^{-1}}$, as the early blue peak should not contain large amounts of lanthanide (Metzger 2017) and an expansion velocity of $0.2 \times$ c. With these values, we obtain an ejected mass of $\approx 3 \times 10^{-3}$–$10^{-2}\,M_{\odot}$. However, the equation we used is an approximation, and more careful models are needed. Comparing the DLT40 light curve with several kilonova models (see Figure 3), we found two models evolving as fast as DLT17ck, which we describe below. The model by Metzger et al. (2010; Met10) assumes a radioactive-powered emission and an ejected mass of 10^{-2} $M_{\odot}$, an outflow speed of $v = 0.1c$, and an iron-like opacity; the model by Barnes & Kasen (2013; B&K) assumes an ejected mass of 10^{-3} $M_{\odot}$, a velocity of 0.1 c, and a typical lanthanide opacity. Both models are consistent with the ejected mass that we computed above, and support the kilonova interpretation.

[7] The possibility that DLT17ck is not related to GW170817, and exploded prior to the event, is discussed in Section 5.

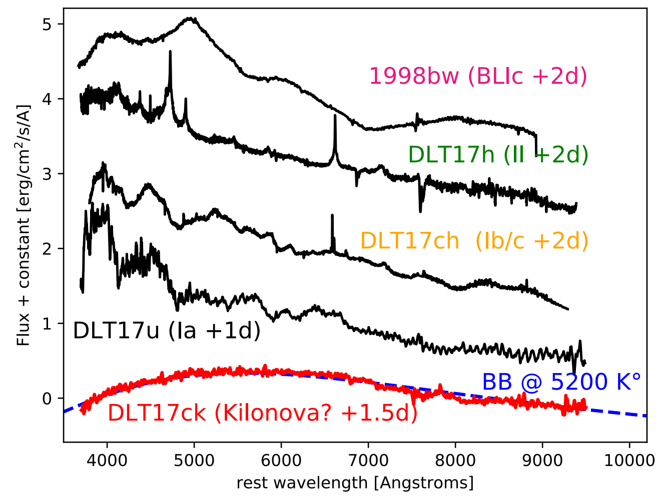

Figure 4. DLT17ck spectrum at 35 hr after the GW170817 compared with spectra of young SNe at similar epochs. DLT17ck is cooling much faster than any previously observed explosive transient. A blackbody fit indicates a temperature of ≈5200 K. Data from DLT17u (FLOYDS), DLT17ch (SALT), DLT17h (SALT), DLT17ck (NTT), and SN1998bw (Danish 1.54 telescope + DFOSC). The presence of an emission feature at ∼7800 Å is suspicious due to the presence of telluric lines close its position.

Further evidence for the kilonova hypothesis comes from the analysis of DLT17ck spectra. Spectroscopic observations were performed by Shappee et al. (2017) about 12 hr after GW170817, showing a blue and featureless continuum. This supports the idea that DLT17ck was discovered young, although a blue and featureless continuum is also common for young SNe II and GRB afterglows. The fast cooling of DLT17ck (and hence the small ejected mass) became evident as more spectra were collected. The extended-Public ESO Spectroscopic Survey for Transient Objects (ePESSTO; Smartt et al. 2015) observed DLT17ck ∼35 hr after GW170817, reporting a featureless spectrum with a much redder continuum than that observed in SN spectra at similar phases (Lyman et al. 2017; see Figure 4). A blackbody fit to the spectrum revealed a temperature of ≈5200 K. Considering a spherically symmetric explosion and a blackbody emission, the radius of the kilonova should have expanded from the radius of a neutron star (a few tenth 10^5 cm) to $\sim 7.3 \times 10^{14}$ cm. Under homologous expansion, this requires a velocity expansion of 0.2 c.

5. Search for Pre-discovery Outbursts in Historical Data

In the standard kilonova model, we only expect a bright EM signature after coalescence. We can test this by looking at DLT40 observations taken before 2017 August 17. NGC 4993 is one of the galaxies monitored by the DLT40 supernova search, observed on average every three days from February 2017 to July 2017 (see Table 1). Our images show no sign of an optical transient down to a limit of $m_r \sim 19$ mag (see Figure 3), corresponding to $M_r \sim -14$ mag at the adopted distance of NGC 4993. Similarly, the field was also observed from 2013 to 2016 from La Silla QUEST on the ESO 1.0 meter telescope with no detection to a limit of $R \sim 18$ mag (Rabinowitz & Baltay 2017).

The last DLT40 non-detection at the position of DLT17ck is on 2017 July 27th (21 days before the LVC event) down to $m_r = 19.1$ mag. Combining this limit with the extremely fast timescale of the transient, its blue continuum in the early spectra, its rapid cooling, and its photometric consistency with

Table 1
Photometric Data for DLT17ck

Date	JD	Mag[a,b]	Filter[c]	Telescope	Date	JD	Mag[a,b]	Filter[c]	Telescope
2017 Aug 17	2457983.493	17.46 0.03	*r*	Prompt 5	2017 Mar 07	2457819.772	>20.90	*r*	Prompt 5
2017 Aug 18	2457983.528	17.56 0.04	*r*	Prompt 5	2017 Mar 10	2457822.595	>19.97	*r*	Prompt 5
2017 Aug 18	2457984.491	18.00 0.06	*r*	Prompt 5	2017 Mar 11	2457823.592	>19.37	*r*	Prompt 5
2017 Aug 19	2457984.510	18.29 0.06	*r*	Prompt 5	2017 Mar 12	2457824.594	>19.39	*r*	Prompt 5
2017 Aug 19	2457985.476	19.34 0.08	*r*	Prompt 5	2017 Mar 13	2457825.586	>19.20	*r*	Prompt 5
2017 Aug 19	2457985.478	19.29 0.12	*r*	Prompt 5	2017 Mar 26	2457838.881	>20.37	*r*	Prompt 5
2017 Aug 21	2457986.503	20.18 0.10	*r*	Prompt 5	2017 Mar 27	2457839.714	>21.14	*r*	Prompt 5
2017 Aug 22	2457987.504	20.92 0.12	*r*	Prompt 5	2017 Mar 28	2457840.717	>20.86	*r*	Prompt 5
2017 Jul 27	2457961.599	>19.84	*r*	Prompt 5	2017 Mar 29	2457841.720	>21.03	*r*	Prompt 5
2017 Jul 27	2457962.495	>19.36	*r*	Prompt 5	2017 Mar 30	2457842.666	>20.74	*r*	Prompt 5
2017 May 15	2457888.762	>19.79	*r*	Prompt 5	2017 Mar 31	2457843.713	>20.83	*r*	Prompt 5
2017 May 16	2457889.751	>19.88	*r*	Prompt 5	2017 Apr 02	2457845.704	>20.90	*r*	Prompt 5
2017 May 17	2457890.796	>19.61	*r*	Prompt 5	2017 Apr 04	2457847.695	>20.73	*r*	Prompt 5
2017 May 20	2457893.500	>19.88	*r*	Prompt 5	2017 Apr 05	2457848.700	>20.87	*r*	Prompt 5
2017 May 21	2457894.562	>20.27	*r*	Prompt 5	2017 Apr 06	2457849.857	>20.63	*r*	Prompt 5
2017 May 22	2457895.545	>20.65	*r*	Prompt 5	2017 Apr 07	2457850.699	>20.24	*r*	Prompt 5
2017 May 28	2457901.715	>19.69	*r*	Prompt 5	2017 Apr 08	2457851.695	>19.74	*r*	Prompt 5
2017 May 29	2457902.548	>20.16	*r*	Prompt 5	2017 Apr 09	2457852.679	>19.56	*r*	Prompt 5
2017 May 30	2457903.547	>20.12	*r*	Prompt 5	2017 Apr 13	2457856.861	>19.45	*r*	Prompt 5
2017 May 31	2457904.544	>20.70	*r*	Prompt 5	2017 Apr 14	2457857.678	>18.41	*r*	Prompt 5
2017 Jun 01	2457905.542	>20.45	*r*	Prompt 5	2017 Apr 15	2457858.666	>20.07	*r*	Prompt 5
2017 Jun 02	2457906.511	>20.24	*r*	Prompt 5	2017 Apr 21	2457864.654	>21.01	*r*	Prompt 5
2017 Jun 02	2457907.498	>20.06	*r*	Prompt 5	2017 Apr 22	2457865.642	>20.93	*r*	Prompt 5
2017 Jun 19	2457923.645	>20.61	*r*	Prompt 5	2017 Apr 23	2457866.760	>21.02	*r*	Prompt 5
2017 Jun 19	2457924.481	>19.65	*r*	Prompt 5	2017 Apr 24	2457867.652	>21.04	*r*	Prompt 5
2016 Dec 21	2457743.834	>20.44	*r*	Prompt 5	2017 Apr 26	2457869.631	>20.67	*r*	Prompt 5
2017 Feb 06	2457790.858	>21.39	*r*	Prompt 5	2017 Apr 27	2457870.626	>20.92	*r*	Prompt 5
2017 Feb 07	2457791.823	>21.34	*r*	Prompt 5	2017 Apr 28	2457871.622	>20.65	*r*	Prompt 5
2017 Feb 08	2457792.826	>21.26	*r*	Prompt 5	2017 Apr 29	2457872.694	>20.66	*r*	Prompt 5
2017 Feb 09	2457793.835	>21.10	*r*	Prompt 5	2017 Apr 30	2457873.618	>20.71	*r*	Prompt 5
2017 Feb 10	2457794.824	>20.58	*r*	Prompt 5	2017 May 01	2457874.615	>20.60	*r*	Prompt 5
2017 Feb 11	2457795.825	>20.33	*r*	Prompt 5	2017 May 03	2457876.665	>20.76	*r*	Prompt 5
2017 Feb 12	2457796.756	>19.90	*r*	Prompt 5	2017 May 04	2457877.594	>20.55	*r*	Prompt 5
2017 Feb 13	2457797.747	>20.16	*r*	Prompt 5	2017 May 05	2457878.606	>20.30	*r*	Prompt 5
2017 Feb 14	2457798.692	>19.85	*r*	Prompt 5	2017 May 06	2457879.577	>20.25	*r*	Prompt 5
2017 Feb 17	2457801.725	>20.37	*r*	Prompt 5	2017 Aug 25	2457990.504	>20.89	*r*	Prompt 5
2017 Feb 19	2457803.828	>20.83	*r*	Prompt 5	2017 Aug 26	2457991.504	>20.37	*r*	Prompt 5
2017 Mar 05	2457817.886	>20.78	*r*	Prompt 5	2017 Aug 26	2457992.489	>19.90	*r*	Prompt 5
2017 Mar 06	2457818.784	>20.91	*r*	Prompt 5	…	…	…	…	…

Notes.
[a] Data have not been corrected for extinction.
[b] Limit magnitude are 5σ detection limit.
[c] *Open* filter calibrated to *r*.

some kilonova models makes it extremely unlikely that DLT17ck can be explained by any kind of supernova unrelated to the GW/GRB event. Rather, all of the evidence favors the fact that DLT17ck was discovered young and is the optical counterpart of GW170817 and GRB 524666471/170817529.

6. Summary and Future Prospects

In this Letter, we presented the discovery of DLT17ck in the error region of the LVC event GW170817 and the *Fermi* short GRB 524666471/170817529. DLT17ck is characterized by a very fast optical evolution, consistent with some kilonova models and with a small ejecta mass (10^2–$10^{-3}\,M_\odot$). Spectroscopic observations conducted about 35 hr after the explosion show a featureless continuum with a blackbody temperature of 5200 K, confirming the fast evolution of DLT17ck compared to the evolution of other transients such as classical SNe. In addition, it is also surprising that, at such a low temperature, no features are visible. We may speculate that this is the result of blending due to the high velocity of the expanding ejecta. Given the coincidence with the LVC event and the short *Fermi* GRB, it is likely the optical counterpart of the merging of two neutron stars in a binary system. This event represents a milestone for astronomy, being the first multi-messenger event from which both photons and GWs have been detected.

The unprecedented characteristics of DLT17ck raise a question as to the rates of such objects. The daily cadence of the DLT40 search can help constrain the rates of kilonovae and other rapidly evolving transients. Details of rate measurements will be presented in a dedicated paper (S. Yang et al. 2017, in preparation), while here we report some of the results related to kilonovae. Using the galaxies within 40 Mpc that we have observed in the last two years, and under the simplifying assumption that all kilonovae have a light curve similar to DLT17ck, we find an upper limit (at 95% confident level) to the rate of kilonovae of $0.48^{+0.90}_{-0.15}$ binary neutron stars (BNS) SNu.[8] For a Milky Way luminosity $\sim 2 \times 10^{10}\ L_{\odot}$, this translates to an upper limit of nine Galactic kilonovae per millennium. This limit is not too stringent, as it is two orders of magnitude larger than the Galactic rate of BNS coalescence of 24 Myr^{-1} estimated by Kim et al. (2015) from known neutron star binaries.

We can convert our luminosity-based kilonova rate to a volumetric rate using the local luminosity density from Blanton et al. (2003). This gives a limit of $9.4 \pm 0.8 \times 10^{-5}$ kilonovae $\mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$. This is consistent with previous limits ($>0.05\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$; Berger et al. 2013), which were based on hypothetical parameters for the BNS optical light curve, and are comparable to the volumetric rate of fast optical transients, $4.8–8.0 \times 10^{-6}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$, found by Drout et al. (2014).

Looking forward to the O3 LVC run in 2018, it is useful to explore strategies to detect EM counterparts of NS–NS mergers. DLT17ck was discovered independently by several groups (e.g., SWOPE and DLT40; Coulter et al. 2017 and Yang et al. 2017b) using the approach of targeting nearby galaxies within the LVC region with small field-of-view instruments (Gehrels et al. 2016). Several wide-field searches were also able to identify the transient (Allam et al. 2017; Chambers et al. 2017; Lipunov et al. 2017; Mller 2017), but only after reports from the targeted searches. This was likely due to the challenge of analyzing a large amount of data in a short period of time.

The small field-of-view strategy, and certainly our discovery, was successful because GW170817/DLT17ck was extremely nearby. The short *Fermi* GRB associated with DLT17ck is the closest ever discovered (see Berger 2014 for a review of short GRBs). However, with the expected increase in sensitivity of the LVC detectors in O3, the volume where NS–NS mergers can be detected will reach 150 Mpc, increasing further to 200 Mpc at full sensitivity (2019+; Abbott et al. 2016a). At these distances galaxy catalogs are incomplete (Smartt et al. 2016) and the sheer number of galaxies will likely favor wide-field strategies. Nonetheless, because the Virgo horizon distance during O3 is predicted to be 65–115 Mpc (Abbott et al. 2016a), the small field-of-view strategy may still be important for the best-localized sources. DLT40 reaches a limiting magnitude of $r \sim 19$ mag in 45–60 s exposures. Taking a more conservative limit of 18.5 mag, we would expect to be able to see sources like DLT17ck out to 70 Mpc. Increasing the exposure time to reach a depth of $\sim$20 mag would allow us to observe BNS mergers in the full range of the Virgo interferometer.

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[8] SNu = $(100\ \mathrm{yr})^{-1}\ (10^{10}\ L^{B}_{\odot})^{-1}$.