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Searching electromagnetic counterpart of gravitational waves

Sheng Yang[1,2*†]

[1] *Department of Physics and Astronomy, University of Padova, Vicolo dell'Osservatorio, 3, I-35122 Padova, Italy*

[2] *Osservatorio Astronomico di Padova, INAF, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy*

[3] *Department of Physics, University of California, 1 Shields Avenue, Davis, CA 95616-5270, USA*

E-mail: sheng.yang@oapd.inaf.it

During the second scientific run (O2) of LIGO/VIRGO collaboration (LVC), an epochal breakthrough occurred when the first binary neutron star (BNS) gravitational wave (GW) event was detected (GW170817) and associated to the weak short GRB170817A detected by the Fermi and Integral satellites. DLT40 was the second of the six groups which independently detected the associated optical kilonova, DLT17ck 11 hours after the GW channel. Multimessenger astronomy, the detection of an astrophysical source with more than one 'messenger' (photons, gravitational waves, neutrinos), has truly begun. In this paper, we report the DLT40 GW follow-up searching results in the LVC O2 season. Two transients have been discovered (DLT17u, DLT17ck) by DLT40 in the process of triggering the GW information and only one is identified as related to the GW event. The paper outlines the DLT40 galaxy prioritization strategy and the procedures developed to search for transient counterpart candidates.

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*Speaker.

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1. Introdution

On Sep 14 2015, the detection of the first gravitational wave signal by the two advanced LIGO (aLIGO) interferometers proclaims the beginning of gravitational wave (GW) era (Abbott et al., 2016a). The next challenging for the astronomy community was the detection of an associate electromagnetic (EM) counterpart, which could provide critical insight into the physics of the event. During its first observing run (O1), aLIGO detected 2 events: GW150914, GW151226 (Abbott et al., 2016c) and 1 possible event, LVT151012 (Abbott et al., 2016b). The analysis of the GW signals revealed that all these events were originated from the merger of binary black hole systems (BBH), which likely do not emit EM radiation. The situation would be different if the system include at least one neutron star (NS), namely binary neutron star (BNS) and neutron star black hole merger (NSBH). Based on our current knowledge, they are predicted to power a short gamma ray burst (GRB) and an optical/near-infrared kilonova (Li & Paczyński, 1998).
The GW signal from the merging of binary neutron stars was detected with the Advanced LIGO and Advanced Virgo interferometers by the LIGO/Virgo Collaboration (LVC) during the O2 run. GW170817 (Abbott et al., 2017b) and its discovery of EM light (Abbott et al., 2017c) opens a new chapter in multi-messenger astronomy era.
In this paper we describe the observational campaign performed by the Distance Less Than 40 Mpc (DLT40) to follow up the GW triggers during LVC O2 by using the Prompt Telescope (Reichart et al., 2005), its results and the prospects for the upcoming years.
In section 2 some details on the DLT40 transient search and the observational strategy are presented. In the following section 3, the results of the search are described. It is noteworthy that DLT40 discovered (among other groups) and monitored the evolution of the kilonova AT 2017gfo/DLT17ck (Valenti et al., 2017) by following the LIGO/Virgo trigger, GW170817 (Abbott et al., 2017b). A brief summary and discussion close the paper in section 4.

2. DLT40 SN search and DLT40 GW observational strategy

DLT40 is designed as a one-day cadence supernovae (SNe) search, monitoring galaxies in the nearby universe ($D \lesssim 40\,\mathrm{Mpc}$) with the goal of discovering and researching SNe at very early phase. Running continuously since September 2016, DLT40 is observing $\sim$500 galaxies every night by using a 40 cm PROMPT telescope at the Cerro Tololo Inter-American Observatory (CTIO). The field of view (FoV) is $10 \times 10\,\mathrm{arcmin}^2$, which is suitable to map nearby galaxies down to a limiting magnitude of $r \sim 19\,\mathrm{mag}$ in 45 s exposures (without filter). The DLT40 targets catalog includes galaxies from the Gravitational Wave Galaxy Catalogue (GWGC; White et al., 2011) at declination < 20 degrees, with an absolute magnitude $M_B < -18\,\mathrm{mag}$, galactic extinction $A_V < 0.5\,\mathrm{mag}$ and recessional velocity $v_r < 3000\,\mathrm{km\,s}^{-1}$ (corresponding to $D \lesssim 40\,\mathrm{Mpc}$). These cuts leave a sample of $\sim 2,000$ bright galaxies, all with estimates of distance, absolute magnitude and apparent diameter. The DLT40 data are processed by an automatic pipeline in nearly real time. Pre-reduced images are transferred within ~ 1 minute to our dedicated server. New candidates are detected by image subtraction with respect to a template image using `Hotpants` (Becker, 2015). The list of candidates are available for scanning by the DLT40 group within a few minutes after acquisition.
Since the quick response of the Prompt telescope is ideal to observe fast transients in accor-

dance with the GW related transients (kilonova or GRB afterglow), DLT40 decided to observe LIGO/Virgo uncertainty region during the O2 observing run. The large uncertainty of GW source localization is very challenging for the EM follow up. DLT40 follows the targeted approach presented in Gehrels et al. (2016), that performs pointed search of selected galaxies in the high probability GW sky box. Once an available LIGO/Virgo alert is announced by LVC through GCN system, the released Healpix (Górski et al., 2005) map is used by the DLT40 pipeline to cross matched the sky box with our own galaxy catalogue. A galaxy prioritization algorithm is developed to maximize the follow-up efficiency, in order to cover the higher probability from the GW localization map and more mass from the galaxy catalogue (assuming compact object mergers follow the mass distribution). The detailed discussion of the galaxy selection and scoring process can be found in a companion paper (Yang et al, in prep). The standard DLT40 exposure per frame is 45 sec so that the typical number of observed frames per night is around 500. The top ranking galaxies in the scoring list reserve a higher priority to be observed. A cut would be employed when the GW uncertainty is large in order to limit the number of targeted galaxies less than 500. Depending on the type of GW source and the predicted time scale of the corresponding EM emission, we decide the followup monitoring time scale: 2 weeks for merger events and 3 weeks for burst events.

3. DLT40 GW searching results for O2 triggers

LIGO O2 ran from 2016 November 30 to 2017 August 25, with Virgo joined on 2017 August 1. Several triggers were issued by LVC for follow-up to the EM community and among them, we followed ten triggers. Two transients were discovered by DLT40 in their uncertainty regions.
One SN Ia, SN2017cbv/DLT17u (see details in a companion paper, Sand et al in prep) was found in NGC5642 which is one galaxy inside G275404 on 2017 Mar 8 while our follow-up observations with Las Cumbres Observatory telescopes exclude that SN2017cbv is related to the GW event.
The other transient DLT17ck, classified as a kilonova in Pian et al. (2017), was detected in NGC4993, which is a galaxy selected from GW170817 (Abbott et al., 2017b,c) and Fermi GBM trigger GRB170817a (Goldstein et al., 2017). As part of the DLT40 GW follow-up search, we prioritized observations of 20 galaxies of the LVC error-box and the 31 most luminous galaxies in the *Fermi* region. DLT17ck was then detected by DLT40 about 11 hours after the GW signal at RA=13:09:48.09 and DEC=-23:22:53.4.6, 5.37W, 8.60S arcsec offset from the centre of NGC 4993 (Valenti et al., 2017), as one of the six optical follow-up groups which independently detected this kilonova, AT 2017 gfo (Abbott et al., 2017c; Coulter et al., 2017; Valenti et al., 2017; Tanvir et al., 2017; Lipunov et al., 2017; Soares-Santos et al., 2017; Arcavi et al., 2017), see Fig. 1.
Yang et al. (2017) used the observed light curve of DLT17ck to constrain the rate of BNS mergers to less than $10^{-4} Mpc^{-3} yr^{-1}$. For such fast transient, DLT40 need to be operated for $\sim$ 18.4 years in order to independently discover a kilonova without GW information.

4. Future Prospects

After the instrument update, the advanced LIGO and VIRGO in O3 run would be able to reach deeper for the BNS and NSBH type GW sources (Abbott et al., 2016d). For the pointing galaxy search strategy in O3 season, the incompleteness of galaxy catalogue should be considered.

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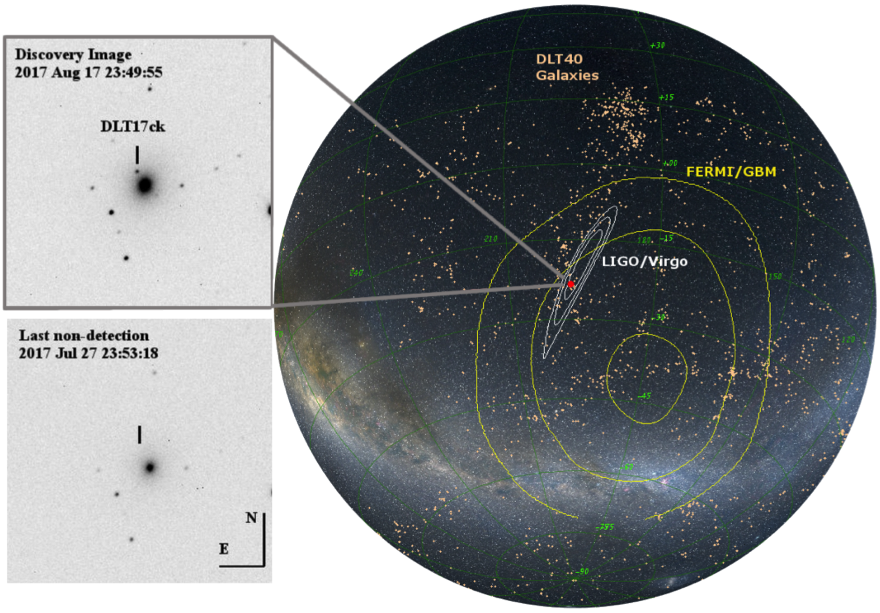

Figure 1: The right panel shows the localization of the GW170817 LVC event using all three gravitational-wave observatories (H1, L1, and V1; 31 deg^2), over-imposed on the *Fermi* localization of GBM trigger GRB170817a. The DLT40 galaxy catalogue are marked in orange. The red point marks the location of DLT17ck and the host galaxy NGC 4993. The inset shows the discovery of DLT17ck in host galaxy NGC 4993 (top left) and the pre-discovery image from 20.5 days prior to merger (bottom left).

GLADE [1], the most complete galaxy catalogue so far, have a good completeness up to 70 Mpc but if one would like to reach deeper, the search based on GLADE would lose some faint galaxies while the large FoV search would be the only choice. In O3 run, the LIGO limit towards BNS source is predicted as 150 Mpc while 65?80 Mpc for VIRGO (Abbott et al., 2016d). If all kilonovae would be as bright as DLT17ck, with the current DLT40 observing strategy, we could detect kilonovae within a distance of 70 Mpc. In order to cover the full Virgo volume (85 Mpc), we would need to go 0.4mag deeper (to a limiting magnitude 19.4 mag), hence increasing the exposure time by a factor of 2.2; this would still allow us to observe $\sim$ 230 galaxies during a single night.

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