The observations of GRB afterglows and the plan to search for optical counterparts of gravitational wave events

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Abstract Here we give an overview of the follow-up campaign of the gamma-ray bursts. And then we give an introduction about GWAC project which is aiming to detect the prompt emission with high-cadence photometry and large field of view monitoring. Besides, we also present our plan to search for the associated counterparts of gravitational wave events in the optical during the O3 run.

Keywords: Gamma-ray Burst, Gravitational Wave, Afterglow, Optical Counterpart, Follow-up Observations

1. Introduction

Gamma-ray bursts are the intensive flashes in high-energy in the deep universe. It consists of two classes, one is long-duration, soft spectral burst, the other is the short-duration, hard burst, separated by the duration of two seconds for their high-energy prompt emission. It is expected that there is afterglow emission in multi-wavelength for both types of gamma-ray bursts. A large fraction of GRB X-ray afterglows shows that there is a very steep decay attributed to the curvature effect and followed by a shallow-decay phase. After that, the afterglow would evolve into the normal decay phase, which is interpreted to be caused by the interactions between the relativistic shock and medium around a GRBs. About 90% of X-ray afterglow emission of GRBs were detected by Swift XRT (e.g. [5]) and about 50% of optical afterglow were detected by telescopes all over the world. The successful detection of multi-wavelength afterglows could provide fruitful information of GRB science, including the high precise localization, the inner physics of relativistic jets, distance, and burst environment, etc. On the other hand, only a few GRBs were detected successfully in the optical band during their prompt emission. Nevertheless, these successful observations of prompt emission have revolutionized much of our knowledge on the GRB science. Taking the naked-eye burst GRB 080319B as an example, it is the brightest GRB up to now, whose peak magnitude during the prompt emission is as high as ~5.3 magnitude in the visible band (e.g. [1]). The non-delayed and high temporal resolution observations of prompt optical emission of GRB 080319B by several ground-based wide-field optical monitor systems, including Pi of the sky and TORTORA (e.g. [1]), make the burst possible for revealing the detailed structure of optical emission, shedding light on the behavior of the burst internal engine (e.g. [3]). With these observations, people are able to study the effect of environment (e.g. [4]) and the radiation mechanism in the inner area of relativistic jets (e.g. [2]).

At least for a friction of short bursts, people believe that they are related to the gravitational events, as a result of the merger of a binary of neutron-black hole or neutron star-neutron star. One of the promising counterpart in the optical is the kilonova/macronova, which is emission powered by radioactive decays of r-process nuclei and it is one of the most promising electromagnetic counterparts of gravitational wave sources (e.g. [22]). Up to now, only several kilonova candidates were found by modeling multi-wavelength light curves of GRB afterglows (e.g. [23]), except for one case, AT2017gfo (e.g. [14]), which was confirmed to be associated to GW170817 and GRB 170817A.

Here we give an overview of the GRB follow-up observations by the TNT telescope in China. In the second part, we give an introduction about the GWAC project which is aiming at detecting the prompt emission with high-cadence photometry and large field of view monitoring. Finally, we present our plan to search for the associated optical counterparts of gravitational waves by follow-up observations.

2. TNT to follow-up the Swift GRBs

TNT is the Tsinghua University-NAOC 0.8m telescope, which is located at Xinglong station (e.g. [6]), northeast of Beijing with a distance of about 120 kilometers. As one of most primary observing stations of National Astronomical Observatories, Chinese Academy of Sciences (NAOC) (IAU code: 327, coordinates: 40°23′39″ N, 117°34′30″ E), the average altitude of the Xinglong station is bout 900m. The mean and media seeing values of the Xinglong station are 1.9 arcsec and 1.7 arcsec, respectively. There are more than 100 photometric nights and about 230 observable nights per year on average. The sky brightness is about 21.1 mag/arcsec^2 in V band at the zenith. Xinglong station has more than 8 telescopes with aperture larger than 0.5 meters, including the 2.16m optical telescope (e.g. [17]).

A PI 1340*1300 CCD is equipped for TNT. The focal ratio of TNT is f/10, giving a field of view of 11.4*11.1 arcminutes. The pixel scale is 0.52 arcsecond. A set of the Johnson-cousin filters UBVRI are equipped for this photometry system. A rapid follow-up system is developed for observations of GRB afterglows for TNT telescope (e.g. [7]). With this system, more than 130 Swift GRBs have been followed and the optical afterglows have been detected for about 50% of these observed GRBs.

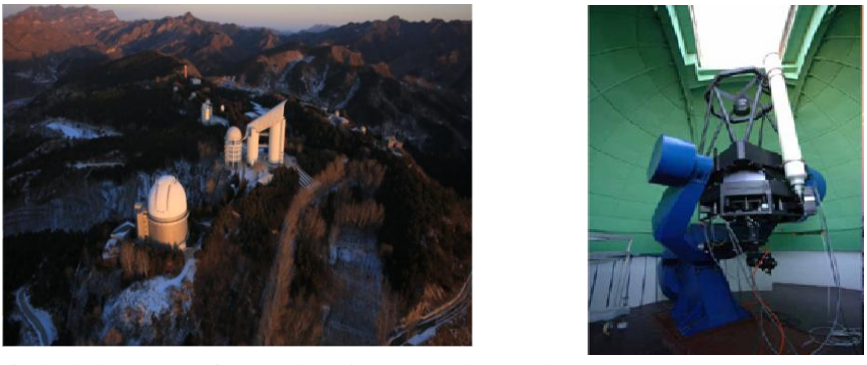

Fig1. *Left: The bird's eye view of the Xinglong observatory, China. Right: The 0.8m TNT optical telescope. Adapted from the website of Xinglong station (e.g. [6])*

When a GRB alert is received, TNT could start the multi-band follow-up observation in 1-2 min since the burst trigger with a pre-defined strategy. In case that the optical afterglow of a GRB is detected and its emission is brighter than 16 magnitude in R band, a low-resolution spectroscope observation by the 2.16m telescope would be requested. The typical delay time for the follow-up observations by the 2.16m telescope is 10-30 min. As done for GRB 140629A (e.g. [8]), the brightness of about 15.3 mag was measured by TNT at the time of about 500 sec after the burst. After a request, a spectroscopic observation was obtained by the Xinglong 2.16m telescope at about one hour after the burst time. The redshift of $z=2.275$ was derived based upon some absorption lines (e.g. [8]), such as CIV λ 1549. After the joint analysis by modeling the optical and X-ray afterglows in the framework of standard synchrotron external shock model (e.g. [9]), the main sciences for GRB 140629A in the following are derived:

1) It follows the standard forward shock model in the thin shell case.
2) The ambient density around the GRB is 60 ± 9 cm^{-3}.
3) The opening angle of jet is very narrow, which is about 0.04 radian.
4) The GRB radiating efficiency is as low as 0.24%, likely indicating a baryonic-dominated ejecta of this GRB.
5) It does not follow the Ghirlanda relation (e.g. [10]) confidently, but fully agrees with Liang relation (e.g. [11]).

3. GWAC to measure the prompt optical emission

In order to measure the temporal properties of the prompt optical emission and the afterglow of all kinds of GRBs at very early phase, an observation system with a very fast slewing or very angle monitoring shall be employed. GWAC (Ground-based Wide Angle Cameras), after its fully setup, would have a capability to monitor ~5000 square degrees of the sky in the cadence of 15 seconds. As a key part of facilities of the future Chinese-French space mission SVOM (Space-based multiband astronomical Variable Objects Monitor, e.g. [14]), the full system of GWAC consists of 10 units. One unit consists of one mount and four cameras. The diameter of each camera is 18cm. Four cameras are mounted in each mount. The magnitude limit is V~16.5 mag with an exposure time of 10 seconds in the moonless night, and V~15.5 mag in the full moon phase. 4k*4k e2V CCD is equipped for each camera, giving a pixel scale of 11.7 arcsec. No filter is equipped in order to increase the detection sensitivity.

The prototype of GWAC was set at Xinglong station, near the dome of the TNT telescope. At present, three units are running normally every night. With the support of a powerful database, a real-time pipeline for short-duration transient detection is developed for GWAC system based on the catalog crossmatch from the object catalog obtained from GWAC observed stacking image and Astronomical distributed catalogs, such as the USNO B1.0 catalog and Gaia dr2 catalog.

Two 60cm optical telescopes with a field of view of 19 arcmin for each and one 30cm optical telescope with a field of view of 1.9 square degrees are also setup in the same dome of GWAC in order to make fast and multi-wavelength follow-up for any transient candidates detected by GWAC. With these follow-ups, it is more easy for people to valid the transients, to measure their higher precise locations, and to obtain the color changes and to monitor the evolution of light curves. Besides, these successful follow-ups also provide alert for scientists to decide whether spectroscopic follow-up observation by the 2.16m telescope and others is needed. More detailed description was presented (e.g. [13]).

Fig2. *GWAC and its follow-up telescope, including two 60 cm telescopes and one 30 cm telescope. Currently, all these are set at Xinglong station, NAOC, China,*

Besides, an automatic follow-up system is also developed for GWAC system to detect the afterglow of GRBs triggered by Swift and Fermi, though there are still no positive detections for GRB afterglows up to now. However, with optimization of the system including hardware and software, the science is believed to be on the way.

4. Search for the optical counterparts from GRBs to GWs

During the O1 and O2 observation campaigns, only one gravitational event GW170817 (Abbott, B. P., et al., 2017) was originated from the merger of binary neutron stars and its counterpart GRB 170817A (e.g. [15]) in high energy was found by the space observatories Fermi and Integral. And its optical counterpart kilonova AT2017gfo (e.g. [14]) was also detected by variety of telescopes in the worldwide. Apart from this one, other gravitational events were considered to be results of the merger of binary of black holes (BBH). During the O1 and O2 epochs, nine BBH gravitational wave events (e.g. [13]) in total were followed by the prototype of GWAC, Mini-GWAC. Particularly, GW151226 was the only one and the first event for Mini-GWAC to search for any possible optical counterparts related to the gravitational events. Eight other GW events were observed by our system during the O2 run as shown in Fig 3. The typical upper limit for all observations for Mini-GWAC was 11-12 magnitude in R band. It is noted that among these follow-ups, the observations by Mini-GWAC for GW170104 started soon in minutes after the alert, and about 2 hours after the event. The sky coverage of GW170104 by Mini-GWAC was about 84.4% of probability which was the largest probability coverage in shortest latency for all observations in the worldwide.

No credible optical transient was found in our images during the O1 and O2 runs. There might be two reasons. One is the nature of these GW events. Nine GW events observed by our system were originated from the merger of binary of black holes. The electromagnetic counterparts from BBH is highly uncertain (e.g. [18], [19], [20], [21]). Secondly, the sensitivity of the mini-GWAC telescopes was not enough to detect relatively faint transients such as the kilonova emission like AT2017gfo (e.g. [14]).

The optimization is going on, we will utilize the GWAC system to search for the kilonova-like transients during the O3 run. The diameter of the GWAC camera is 18cm, compared to that of D=7cm for Mini-GWAC, the detection sensitivity could be increased to V~16mag in a single frame. Since the brightness of AT2017gfo evolves with 1 magnitude per day during its peak time, it is not advantage to search these relatively slowly fading transients in very short cadence of 15 seconds. The image stacking would increase the sensitivity of GWAC to about V~18mag (e.g. [13]), which increases the possibility to detect optical counterparts of GW events.

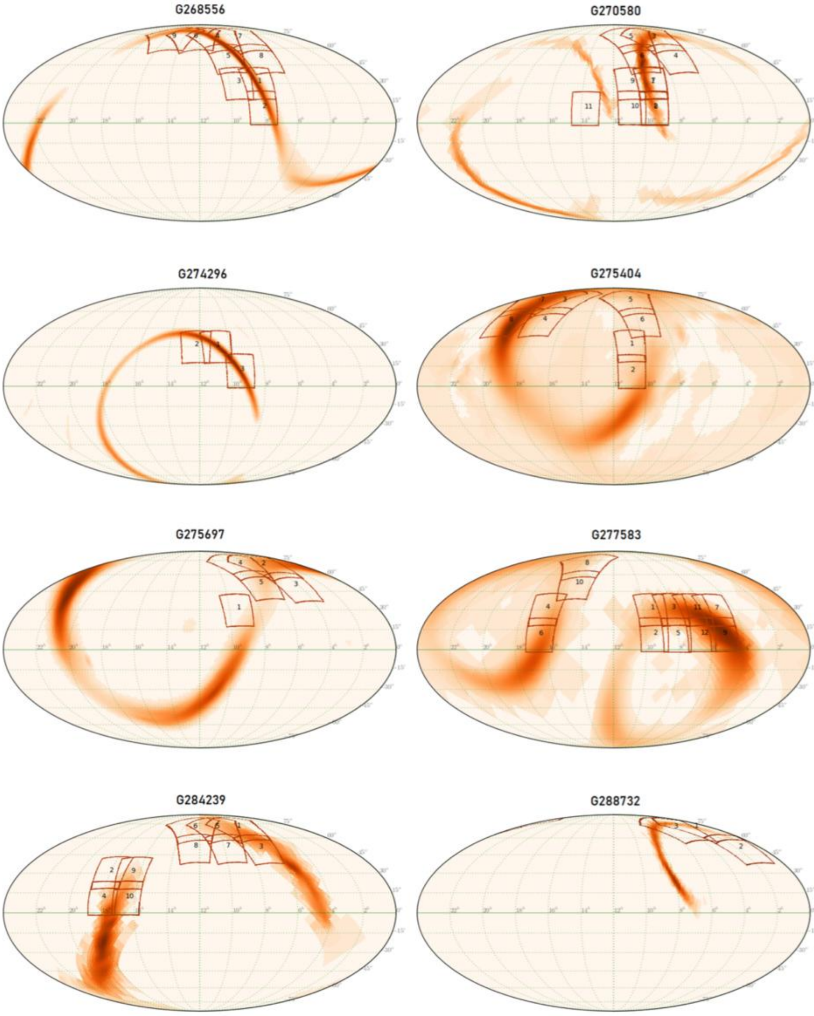

Fig 3. *The skymaps of the eight gravitational wave events followed by GWAC system during O2 run, adapted from [13]. All observation grids are shown with the red squares each of them identified with a grid ID.*

5. Conclusion

Here we present an overview of the follow-up of GRBs mainly carried out by the 0.8m Tsinghua and National astronomical observation telescope (TNT) in China. The follow-up campaign mainly focuses on the well localized GRBs triggered by Swift for more than 12 years since 2006. The follow-up observations to search for the optical counterparts from gravitational wave events during the O1 and O2 runs are also briefly presented. Furthermore, we also introduce our next plan for the follow-up observations of gravitational wave events detected by LIGO/Virgo during the O3 run.

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