Optical and NIR Observations for Gravitational Wave Event GW170817

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INTRODUCTION

Following the first detection of a gravitational wave (GW) from a binary black hole (BBH), a couple of reports of GW detections followed. The next milestone for the GW experiment became the detection of a GW from a compact binary coalescence, including a neutron star (NS). The system including an NS is interesting because accompanied various electromagnetic (EM) emissions such as gamma-ray, X-ray, optical and near-infrared (NIR) and radio emissions are expected. An optical and near-infrared (NIR) emission driven by the radio-active decays of r-process nuclei, due to a "kilonova" or "macronova", is one of the most promising EM counterparts (Kasen et al. 2013, ApJ, 774, 25; Barnes & Kasen, 2013, ApJ, 775, 18; Tanaka & Hotokezaka, 2013, ApJ, 775, 113; Tanaka et al. 2014, ApJ, 780, 31; Metzger & Ferná ndez 2014, MNRAS, 441, 3444; Kasen et al. 2015, MNRAS, 450, 1777). Optical and NIR observations give us a hint in understanding the origin of r-process elements in the Universe because emission properties depend on the ejected mass and abundances of r-process elements.

GW170817

On August 17, 2017, 12:41:04 GMT, LIGO (Laser Interferometer Gravitational-Wave Observatory) Hanford Observatory (LHO) detected a GW candidate from compact binary coalescence likely including an NS. The subsequent analysis with three available detectors including LIGO Livingston Observatory (LLO) and Virgo provided the localization to 33.6 deg^2 and 40(+/−)8 Mpc for 90% of the credible region (Abbott et al. 2017, Phys. Rev. Lett., 116, 241103). It was, at that time, the smallest localization accuracy ever achieved. In parallel, a Fermi-GBM (Gamma-ray Burst Monitor) trigger, approximately 2 s after the coalescence, was reported, whose localization partly overlapped with the GW localization. The coincidence in time and position of the GW and gamma ray encouraged extensive observations for locating and following-up EM emissions from the source of the GW. The event was later named GW170817.

LOCATING A TARGET

Locating an optical and NIR counterpart from the localization with an accuracy of 30 deg^2 is still challenging because a typical field-of-view in optical and NIR observation is an order of 0.1 deg^2 while the widest is several deg^2. To complete the error region with a typical camera it requires more than 100 times tiling observation, which is not practical. Kanner et al. (2012, ApJ, 759, 22) and Gehrels et al. (2016, ApJ, 820, 136) proposed the idea to search for EM counterparts to GW sources using a galaxy catalog, assuming that compact merger events should occur within or close to their host galaxies. This idea significantly reduces the number of galaxies that should be observed to an order of 10 for nearby events less than 100Mpc.

Coulter et al. (2017, Science, 358, 6370, 1556) reported the first discovery of a transient, SSS17a, within the localization area. They used a 1.0m Swope Telescope at Las Campanas Obserevatory in Chile with this galaxy strategy. From 46 candidate galaxies combined in their 12 images, they found a transient which was not a previously known asteroid or supernova (SN). Similar detection reports followed subsequently (e.g. Valeneti et al.

2017, ApJ, 848, 24 and Soares-Santos M. et al. 2017, ApJ, 848, 16).

FOLLOW-UP OBSERVATION

Although a candidate was detected, the nature of SSS17a was still unclear. Observing the evolution of brightness (light curve) and color was important to reveal its nature – i.e. whether the transient was a kilonova or not. However, poor visibility of SSS17a prevented us from continuing the observation at the same observatory. A relayed observation with many observatories, distributed all over the world, was key for this follow-up observation. Many observatories and groups, including those located in the Asia Pacific region, made significant contributions to reveal this event. Over 3500 researchers participated in this follow-up observation (Abbott B. P., et al., 2017, ApJ 848, L12). Here we briefly introduce papers led by authors based in countries in the Asia Pacific region.

J-GEM (Japanese Collaboration for Gravitational-Wave Electro-Magnetic Follow-up) conducted follow-up observations with facilities distributed around the world (including the Southern Hemisphere, where the visibility was better) that are operated by, or where significant contributions are received from Japanese institutes (Utsumi et al. 2017, PASJ, 69, 6, 101). Imaging observations with IRSF (Infrared Survey Facility) at the South African Astronomical Observatory, Subaru Telescope at Maunakea in the US, and MOA-II and the 61cm Boller & Chivens telescope in New Zealand successfully revealed the light curve and evolution of color in Optical and NIR (Figure 1). The rapid decline and color of their 15 day multi-wavelength observations is consistent with the kilonova model with the ejecta mass of 0.01 Msun from the merger containing r-process elements. On the other hand, the brightness was 2 orders of magnitudes brighter than the expected, which suggests that higher mass ejection or additional energy input is required. Further theoretical investigation confirmed that higher mass ejection with 0.03 Msun could explain this tension (Tanaka et al. 2017, PASJ, 69, 102). However, they still showed blue excess in an early phase of an SED (spectrum energy distribution), which requires an additional r-process free component. They also conducted a blind survey to find any other possible candidate with a very wide field optical camera (Hyper Suprime-Cam) at the Subaru Telescope, (Tominaga et al., 2017, PASJ, 70, 28).

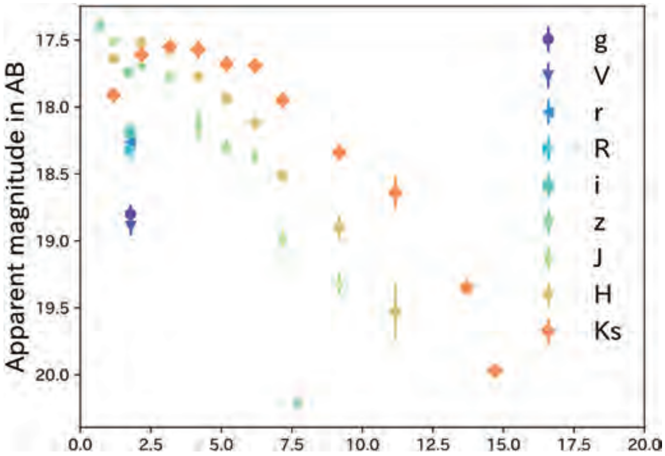

Fig. 1: A light curve obtained by J-GEM observation. From g to Ks, color changes from blue to red, respectively.

The Australian-led group conducted follow-up observations with 14 Australian telescopes and partner observatories as part of Australia-based and Australian-led research programs (Andreoni et al., 2017, PASA, 34, 69). They obtained optical imaging and spectroscopy, mid-infrared imaging and radio imaging. Their spectroscopic observation shows no significant optical emission lines. They also tried to interpret their photometric light curves with several different models, and concluded these properties were consistent with a combination of the expected kilonova and the blue kilonova model which is an r-process elements free model.

FUTURE PERSPECTIVES

It is still unclear whether the BNS generates enough amounts of r-process elements in the Universe. Accumulating observations of BNS with GWs provide statistical studies to answer the question. Understanding behavior in the early phase of a kilonova is also important because the early phase of SSS17a has deviated from the theoretical model. To increase the chances for prompt observations, the construction of an observatory is a possible strategy. Also, prompt observation with multiple colors is another route to explore the mechanism of kilonovas.

In an international effort between Japan's Hiroshima University and China's National Astronomical Observatories, the Chinese Academy of Sciences, a new astronomical observatory project, HinOTORI (Hiroshima University Operated Tibet Optical Robotic Imager; http://hinotori.hiroshima-u.ac.jp), is ongoing (Figure 2).

HinOTORI is a 50cm Ritchey-Chretien telescope with a 3 color simultaneous imager in SDSS-u (359.7nm), R (653.0nm), and I (790.7nm), which is a dedicated telescope for observing an EM emission for GW. The operation of this telescope will be fully automated. As SSS17a is unexpectedly blue in its very early phase, within a few days from merger, compared to a single component model with lanthanide elements, the u-band capability will provide clues to understanding unknown behavior in the early phase. The observatory is being constructed in the Ali Observatory of NAOC (Yao et al., 2012, SPIE, 8444, 13), which is located at the west end of China. The altitude of the observatory is at 5100 m. Although the measured site conditions are limited, early data and following model calculation suggest the site conditions are promising (Ye et al. 2016, MNRAS, 457, 1 and references therein). The HinOTORI telescope is going to be operational in 2018. Also, the next LIGO-Virgo run will start in the end of 2018. The combination of an improved EM observation network and increased sensitivity of the GW detectors will soon provide many opportunities to investigate kilonovas.

Fig. 2: Inside of the HinOTORI Observatory.

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