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J-GEM electromagnetic follow-ups for gravitational-wave events in O3 and O4

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The gravitational-wave (GW) detectors LIGO and Virgo sent out 56 GW alerts during the third observing run (O3). The Japanese Collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM) performed optical and near-infrared observations to identify an electromagnetic (EM) counterpart. To facilitate follow-up observations, we have developed a web-based system to share information on candidate host galaxies and the status of the observations. Candidate host galaxies are selected from the GLADE catalog with a weight of 3D GW localization map. Using these systems, we performed galaxy-targeted and wide-field blind surveys, real-time data analysis, and visual inspection of transient candidates. We conducted galaxy-targeted follow-up observations of 23 GW events during O3. We successfully started observations for 10 GW events within 0.5 days after the GW detection. This result demonstrates that our follow-up observation has the potential to constrain EM radiation models for a merger of binary neutron stars at a distance of up to $\sim$100 Mpc with a probability area of < 500 deg^2. We have also performed the follow-up for the fourth observing run (O4).

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1. Introduction

Depending on the nature of a coalescing source, a gravitational-wave (GW) emission may accompany electromagnetic (EM) radiation. An identification and observation of the EM counterpart to a GW signal are important for understanding the physics of the GW source.

Identification of an EM counterpart to a GW event was achieved for the first time for GW170817 reported by LVCs (Laser Interferometer Gravitational-Wave Observatory and Virgo Collaboration) [1, 2]. The optical counterpart (AT 2017gfo) was identified by galaxy-targeted surveys 10.86 hours after the GW detection [3]. The optical emission of AT 2017gfo rapidly declined, while the near-infrared (NIR) emission lasted relatively longer (e.g., [4]). The optical spectra of AT 2017gfo rapidly evolved from blue to red [5, 6]. These properties are clearly different from those of supernovae.

When a binary neutron star (BNS) coalesces, a portion of matter of the merger material is ejected into interstellar space. In this material, r-process elements including lanthanides are likely to be synthesized. This matter gives rise to thermal emission mainly in the optical and infrared bands, which is powered by the radioactive decay of the r-process nuclei, called a "kilonova." The observed temporal evolution of the optical and near-infrared (NIR) emission of AT 2017gfo was consistent with simple kilonova models[7]. However, the blue component seen in the early phase may not be fully reproduced by the simple kilonova model. To explain the blue emission, two models were proposed: (1) a kilonova model with a higher electron fraction [8], or (2) a cocoon generated by interactions between the NS ejecta and the jet that powered the emission from radio to gamma-ray wavelengths (e.g. [9]). Both models can explain the light curve observed after 0.5 days, but these models predict different brightnesses at < 0.5 days [10]. Thus, early-phase observations are required to determine the origin of the optical blue emission.

An early-phase identification of an EM counterpart is, thus, important to understand the radiation mechanism of the GW source. However, the identification is not easy, because of a large localization area of GW signal obtained by GW detectors and limited fields of view (FoVs) of EM instruments. A wide-field blind survey using a wide FoV instrument can search any EM counterpart associated with the GW source, even without any association with a host-like galaxy. Another approach is to survey cataloged galaxies within the 3D localization map under the assumption that the EM counterpart is located close to or on a galaxy [11]. This approach is called a galaxy-targeted survey.

2. Telescopes and instruments

The Japanese Collaboration for Gravitational-wave ElectroMagnetic follow-up (J-GEM) has conducted optical and NIR follow-up campaigns of GW events since 2015 [4, 12–18]. J-GEM consists of a consortium of facilities that cover the optical, NIR, and radio wavelengths. To enable rapid follow-up observations for GW sources detected at arbitrary time from various directions, we form a network of multi-latitudinal and longitudinal observatories. Our network enables an effective search for a transient in a large GW localization area by involving multiple telescopes and cameras. The telescopes used for EM follow-up are listed in Table 1. With these multi-located telescopes, we are able to perform stable and quick follow-ups avoiding the effects of bad weather (figure 1). In O3, optical data were obtained with nine instruments on eight telescopes, and NIR data were obtained with four instruments on four telescopes.

Figure 1: Optical, infrared, and radio telescopes in the J-GEM network.

3. Procedure of EM follow-up observations

Alerts of GWs issued by LVCs are retrieved through our web system called "planner." This system calculates a 3D map that shows the probability of the existence of GW sources based on the localization area of the GWs and estimated source distances. The planner extracts the candidate host galaxies of the GW sources from the galaxy catalog, Galaxy List for the Advanced Detector Era (GLADE) [19], which are within the calculated map.

Since the arrival probability of GWs can be calculated using the positions of the extracted galaxies, the observation priority for the catalog of candidate host galaxies is determined by multiplying the B-band luminosity of each galaxy. Each galaxy is ranked based on the calculated priority, and the galaxies to be observed by each telescope are selected from the ranked catalog of candidate host galaxies.

Each telescope conducts observations on the target galaxy until the required detection limit is reached. The obtained data is then processed by subtracting the dark and flat-fielding it. The World Coordinate System (WCS) information of the image is calculated using the star pattern within the FoV. In the case of multiple observations made for a target galaxy, the acquired images are combined based on the WCS information.

The resulting composite images are uploaded to a web system called the Image Server, and these images are shared among the J-GEM team. The Image Server retrieves brightness information of the stars in the uploaded image from either the Panoramic Survey Telescope and Rapid Response System (PanSTARRS) catalog or the Two Micron All Sky Survey (2MASS) catalog [20, 21].

Telescope	**Diam. (m)**	**Instrument**	**Mode**
Subaru	8.2	Hyper Suprime-Cam	Imaging
		FOCAS	Imaging, Spectroscopy
TAO	6.5	MIMIZUKU	Imaging, Spectroscopy
		SWIMS	Imaging, Spectroscopy
Seimei	3.8	TriCCS	Imaging
		KOOLS-IFU	Spectroscopy
Nayuta	2.0	NIC	Imaging
PRIME	1.8	PRIME camera	Imaging
MOA II	1.8	MOA-cam3	Imaging
Kanata	1.5	HONIR	Imaging
		HOWPol	Imaging, Spectroscopy
IRSF	1.4	SIRIUS	Imaging
Kiso Schmidt	1.05	Tomo-e Gozen	Imaging
Kagoshima 1m telescope	1.0	Simultaneous imager	Imaging
OAO 91 cm	0.91	OAOWFC	Imaging
B&C	0.61	Tripole5	Imaging
SaCRA	0.55	MuSaSHI	Imaging
MITSuME Akeno	0.5	g, R_C, I_C imager	Imaging
MITSuME Okayama	0.5	g, R_C, I_C imager	Imaging
HinOTORI	0.5	Simultaneous imager	Imaging

Table 1: Specifications of telescopes and instruments in J-GEM

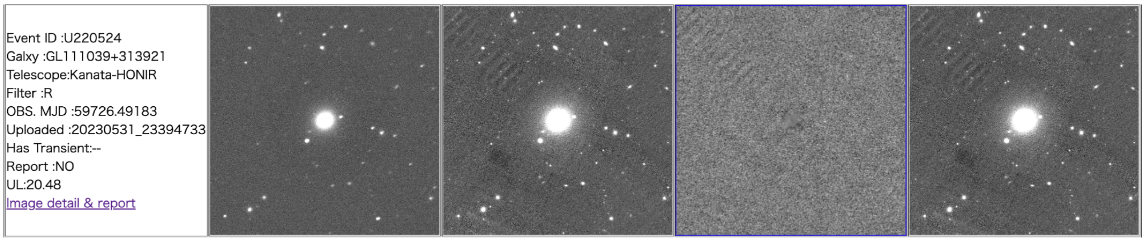
It calculates the zero point of the image based on the brightness of the stars obtained and also determines the detection limit.

A reference image of the same FoV is created by extracting the WCS information of the uploaded image. A subtracted image is then generated by calculating the difference between the acquired image and the reference image. If there is a transient event, it will not be present in the reference image, thus highlighting the transient in the difference image and enabling its identification.

The Image Server displays the uploaded image, reference image, subtracted image, and blinked image (figure 2). The result of a visual check for the presence of a transient in the Image Server is reported to the planner and shared among the J-GEM team. If a transient event is detected, the information is immediately shared with the team, and follow-up observations are conducted by other telescopes.

4. EM follow-ups in O3 and O4

In O3, J-GEM conducted optical and NIR follow-up observations for 23 GW events. Imaging observations were made immediately after receiving GW alerts, focusing on candidate host galaxies



Event ID :U220524
Galxy :GL111039+313921
Telescope:Kanata-HONIR
Filter :R
OBS. MJD :59726.49183
Uploaded :20230531_23394733
Has Transient:--
Report :NO
UL:20.48
Image detail & report

Figure 2: Images of galaxy GL 111039+313921 obtained by Kanata telescope in Image Server. From left to right, panels show observation details, uploaded image, reference image, subtracted image, and blink image, respectively.

within the GW localization areas. The survey observations were performed over several days for each event. For instance, GW190425, resulting from the merger of a BNS, involved the observation of a maximum of 170 galaxies. Similarly, more than 100 candidate host galaxies were successfully surveyed in multiple events. Furthermore, follow-up observations could commence in less than 0.1 day after the occurrence of a GW event. This result indicates the promptness of the J-GEM system in conducting follow-up observations immediately after an event.

From the detection limits obtained by each telescope, we can estimate the detectability for the GW EM counterparts that can be detected by the J-GEM survey observations. The obtained detection limits was distributed around 19 mag, indicating that transients being between 19 and 20 mags are detectable. The peak magnitude of GW170817 at 100 mega-parsec (Mpc) would be approximately 19 mag, indicating that it can be detected by J-GEM survey observations.

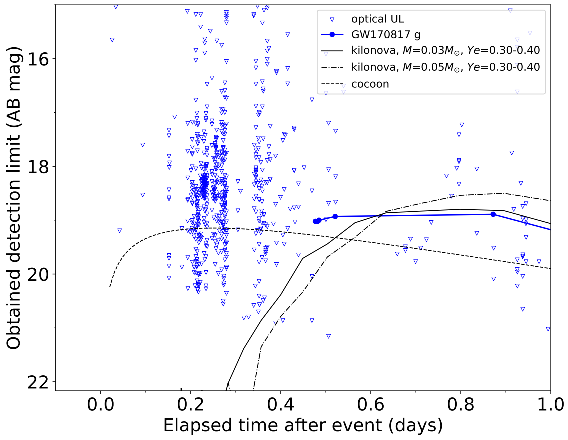


Figure 3: Time series of obtained detection limits with the light curve of GW170817 scaled to a distance of 100 Mpc.

The time series of obtained detection limits is compared with the light curve of the EM counterpart of the GW source. Figure 3 displays the comparison between the light curve of GW170817, scaled to a distance of 100 Mpc, and the time series of detection limits. The detection limits are deeper than the light curve, indicating that the EM counterpart can be detected if we observe the host galaxy of the GW source at 100 Mpc.

The time evolution of EM emission from the merger of BNS, as calculated by the kilonova and cocoon models [22, 23], exhibits differences in periods earlier than 0.5 days. Specifically, around 0.2 days, the obtained detection limit is deeper than the cocoon model's light curve. Therefore, if we detect the EM counterpart around 0.2 days, we can distinguish between the emission models.

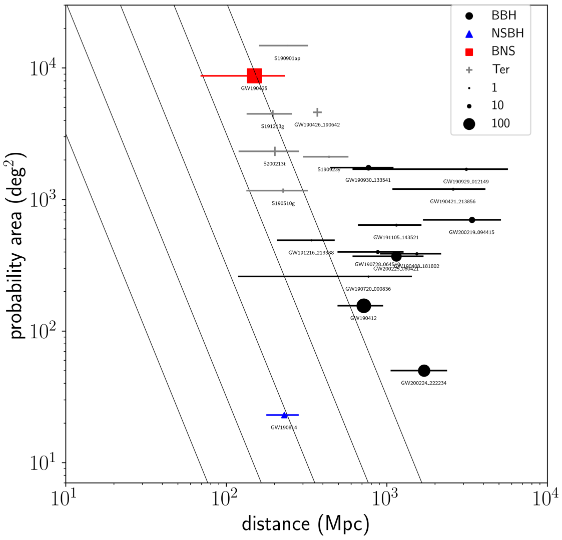


Figure 4: Distribution of numbers of observed galaxies for GW events followed up by J-GEM in the distance–probability area plane. Points are shown for BBH (filled circle), neutron-star black-hole binary (NSBH) (filled triangle), BNS (filled square), and Terrestrial event (cross). The point sizes represent the numbers of observed galaxies within the 3D localization maps of each GW event. Solid lines show the expected numbers of galaxies within the 3D localization map, from left to right, of 1, 10, 100, 1000, and 10 000.

We evaluate the feasibility of detecting an EM counterpart by comparing the observed and expected numbers of galaxies within a GW localization region. The expected number of galaxies within the 3D localization map of a GW source is estimated from a multiplication between the volume and the number density of galaxies (see [16] in details). The number of galaxies within the 3D localization maps for most GW events is estimated to be over 1000 as shown in figure 4. Thus, with our follow-up campaigns, observing all the galaxies within the huge 3D localization maps of such GW events is not feasible. In our follow-up campaigns in O3, the maximum number of observed galaxies was 170. If the localization accuracy is about 500 deg^2 and the distance to the event is ~100 Mpc, a typical number of galaxies is about 100. Therefore, our galaxy-targeted follow-up system is effective for detecting an EM counterpart for a localization area of 500 deg^2 and a distance of 100 Mpc.

Since O4 began in May 2023, a lot of GW alerts have been issued. Most alerts have false alarm rates (FARs) as large as 10^{-6}, but several alerts have detected GWs of astronomical origin with the FARs as small as 10^{-9} or less. Most of the expected types were binary black holes (BBHs), but GW detections from astronomical sources including NSs can be expected. In the first half of 2023, only LIGO have been operated as GW detectors, and the localization areas of detected GWs were large, more than 1000 deg^2 in most cases. The smaller localization areas of GWs are expected after operating Virgo. The J-GEM is conducting EM follow-up of GWs in O4, and will increase the efficiency of EM follow-up as the localization areas of GWs become smaller.

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