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Letter

Letter

J-GEM follow-up observations to search for an optical counterpart of the first gravitational wave source GW150914

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Abstract

We present our optical follow-up observations to search for an electromagnetic counterpart of the first gravitational wave source GW150914 in the framework of the Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM), which is an observing group utilizing optical and radio telescopes in Japan, as well as in New Zealand, China, South Africa, Chile, and Hawaii. We carried out a wide-field imaging survey with the Kiso Wide Field Camera (KWFC) on the 1.05 m Kiso Schmidt telescope in Japan and a galaxy-targeted survey with Tripole5 on the B&C 61 cm telescope in New Zealand. Approximately 24 deg^2 regions in total were surveyed in *i*-band with KWFC and 18 nearby galaxies were observed with Tripole5 in *g*-, *r*-, and *i*-bands 4–12 days after the gravitational wave detection. Median 5σ depths are $i \sim 18.9$ mag for the KWFC data and $g \sim 18.9$ mag, $r \sim 18.7$ mag, and $i \sim 18.3$ mag for the Tripole5 data. The probability for a counterpart to be in the observed area is 1.2% in the initial skymap and 0.1% in the final skymap. We do not find any transient source associated to an external galaxy with spatial offset from its center, which is consistent with the local supernova rate.

Key words: binaries: close — black hole physics — gravitational waves — methods: observational — surveys

1 Introduction

A new generation of gravitational-wave (GW) detectors, Advanced LIGO (Abbott et al. 2016a), Advanced Virgo (Acernese et al. 2015), and KAGRA (Somiya 2012), are designed to detect GWs from mergers of neutron stars (NSs) and black holes (BHs). These new detectors are much more sensitive than ever: with the design sensitivity, the horizon distance will reach ∼200 Mpc for NS–NS mergers and a few Gpc for BH–NS or BH–BH mergers, and many detections of GW events per year are expected (Abbott et al. 2016e).

Detections of electromagnetic (EM) counterparts are essential to studying their astrophysical properties and environments. However, since positional localization with only GW detectors is not accurate, larger than 100 deg^2 during their early observing run (Kasliwal & Nissanke 2014; Singer et al. 2014) and a few 10 deg^2 even in the LIGO–Virgo–KAGRA era (Nissanke et al. 2013; Kelley et al. 2013), it is a big challenge to identify the EM counterparts. To guide surveys for the EM identification, various kinds of EM signals have been theoretically studied over a wide wavelength range, from radio (Nakar & Piran 2011), infrared, optical, and ultraviolet (Li & Paczyński 1998; Kulkarni 2005; Metzger et al. 2010; Tanaka & Hotokezaka 2013), X-ray (Nakamura et al. 2014; Metzger & Piro 2014), to gamma-ray (e.g., short gamma-ray burst: Metzger & Berger 2012). Consequently, we have organized a group to carry out systematic follow-up observations of GW sources using Japanese facilities called "Japanese collaboration for GW EM follow-up (J-GEM)" as part of a larger worldwide EM follow-up effort.

Recently, Advanced LIGO reported on the first detection of the GW event (GW150914: Abbott et al. 2016c). The signal was detected at 09:50:45 UT on 2015 September 14, 4 days before the official start of the first observing run (O1); an alert was delivered via GCN Notices in a machine-readable way at 03:12:12 UT and by e-mail manually at 05:39:44 UT on 2015 September 16. The waveform indicates that the source of the GWs is a merger of two BHs, whose masses are estimated to be $36^{+5}_{-4}\,M_{\odot}$ and $29^{+4}_{-4}\,M_{\odot}$, and that the luminosity distance is 410^{+160}_{-180} Mpc (LIGO Scientific Collaboration & Virgo Collaboration 2016). The position of the source is localized to 590 deg^2 (90% probability). We note that, at the time of the initial alert, a classification of this GW source was not shared with the EM observers and the BH–BH nature was reported after our observations presented in this Letter.

To search for an EM counterpart of GW150914, extensive EM follow-up observations have been performed following the alert (Abbott et al. 2016d, 2016b). In this Letter, we report on optical follow-up observations for GW150914 by the J-GEM collaboration. We refer to a skymap promptly produced with LALInference Burst (LIB: Lynch et al. 2015) as the initial skymap and to the most accurate LALInference (Veitch et al. 2015) skymap distributed on 2016 January 13 as the final skymap. All the magnitudes shown in this Letter are in the AB system.

Table 1. J-GEM telescopes in order of longitude.

Site (telescope)*	Diam. [m]*	Place (long., lat., hgt.)	Instrument‡	FoV	Pixel scale	Note‖
Mt. Johns (B&C 61 cm)	0.61	170.°47 E, 43.°40 S, 1029 m	Tripole5	4.′2 × 6.′2	0.″17	(1)
Mt. Johns (MOA-II)	1.8	170.°47 E, 43.°40 S, 1029 m	MOA-cam3 [1]	1.°31 × 1.°64	0.″58	(3)
Akeno (MITSuME)	0.5	138.°48 E, 35.°79 N, 900 m	(g, R_C, I_C imager)	27.′8 × 27.′8	1.″63	(1)
Kiso (Kiso Schimidt)	1.05	137.°63 E, 35.°79 N, 1130 m	KWFC [2]	2.°2 × 2.°2	0.″946	(3)
Nishi-Harima (Nayuta)	2.0	134.°34 E, 35.°03 N, 449 m	MINT	10.′9 × 10.′9	0.″32	(1)
Okayama, OAO (Kyoto 3.8 m[a])	3.8	133.°60 E, 34.°58 N, 343 m	KOOLS-IFU	14″ ϕ	1.″14	(2)
Okayama, OAO (OAO 188 cm)	1.88	133.°59 E, 34.°58 N, 371 m	KOOLS-IFU	30″ ϕ	2.″34	(2)
Okayama, OAO (OAO 91 cm)	0.9	133.°59 E, 34.°58 N, 364 m	OAO-WFC [3]	28.′4 × 28.′4	1.″67	(1)
Okayama, OAO (MITSuME)	0.5	133.°59 E, 34.°58 N, 358 m	(g, R_C, I_C imager) [4],[5]	26.′9 × 26.′9	1.″52	(1)
Higashi-Hiroshima (Kanata)	1.5	132.°78 E, 34.°38 N, 511 m	HOWPol [6]	15′ ϕ	0.″30	(1)
Higashi-Hiroshima (Kanata)	1.5	132.°78 E, 34.°38 N, 511 m	HONIR [7],[8]	10′ × 10′	0.″30	(1)
Yamaguchi (Yamaguchi[b])	32 × 2	131.°56 E, 34.°22 N, 166 m	6–8 GHz Receiver	–	4′–5′	(1)
Tibet (HinOTORI[a])	0.5	80.°03 E, 32.°31 N, 5130 m	(u, R_C, I_C imager)	24′ × 24′	0.″68	(1)
Sutherland, SAAO (IRSF)	1.4	20.°81 E, 32.°38 S, 1761 m	SIRIUS [9],[10]	7.′7 × 7.′7	0.″45	(1)
Pampa la Bola (ASTE[c])	10	67.°70 W, 22.°97 S, 4862 m	ASTECAM [11]	8.′1 ϕ	20″–30″	(1)
Chajnantor, TAO (miniTAO)	1.04	67.°74 W, 22.°99 S, 5640 m	ANIR [12]	5.′1 × 5.′1	0.″298	(1)
Mauna Kea, MKO (Subaru)	8.2	155.°48 W, 19.°83 N, 4139 m	HSC [13]	1.°5 ϕ	0.″168	(3)

*Comments: [a] to be operated; [b] radio telescope; [c] submillimeter telescope.

†References: [1] Sako et al. (2008); [2] Sako et al. 2012; [3] Yanagisawa et al. (2014); [4] Kotani et al. (2005); [5] Yanagisawa et al. (2010); [6] Kawabata et al. (2008); [7] Akitaya et al. (2014); [8] Sakimoto et al. (2012); [9] Nagashima et al. (1999); [10] Nagayama et al. (2003); [11] Oshima et al. (2013); [12] Konishi et al. (2015); [13] Miyazaki et al. (2012).

‡(1) galaxy-targeted; (2) integral field spectroscopy; (3) wide-field survey.

2 J-GEM observations for GW150914

J-GEM has observing facilities from radio to optical as listed in table 1. They are nicely distributed all over the Earth in terms of the longitudes of the sites. Among them, we utilized two telescopes to carry out two types of optical follow-up observations for GW150914: one is an imaging survey with a wide-field imaging camera, Kiso Wide Field Camera (KWFC: Sako et al. 2012) mounted on the 1.05 m Kiso Schmidt telescope in Japan, and the other is galaxy-targeted observations of nearby potential host galaxies of the GW source with Tripole5 on the 61 cm Boller & Chivens (B&C) telescope at the Mt. John University Observatory in New Zealand. Most of the high probability regions are in the Southern Hemisphere and are difficult to observe with most of our observing facilities. Subaru Hyper Suprime-Cam (HSC: Miyazaki et al. 2012), which has the widest field of view among 8 m class telescopes, was not available after the alert until the beginning of October.

2.1 Kiso KWFC observations

KWFC is a wide-field optical imaging camera on the 1.05 m Kiso Schmidt telescope. The camera consists of eight 2 k × 4 k CCDs and the total field of view is 2.°2 × 2.°2.

The KWFC observations were carried out on 2015 September 18, 4.4 days after the GW detection. We took 180 s exposures for five continuous fields-of-view, approximately 24 deg^2 in total (Morokuma et al. 2016). The observed area is shown in figure 1 and details of the observations are summarized in table 2. The high probability regions in the skymap visible from the site during the night are almost toward the Sun and the target fields are observable only at very low elevation [high airmass: sec (z) > 3, where z is the zenith distance] before sunrise and during the astronomical twilight. Therefore, we chose the i-band filter to avoid high sky background due to the Sun as much as possible.

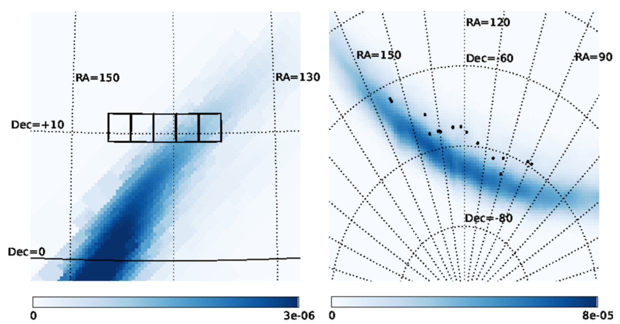

Fig. 1. Final skymap (LALInference) for the GW150914 localization and the observed regions with KWFC (left) and Tripole5 (right). The color map is shown in units of probability per HEALPix (Górski et al. 2005) pixel of $N_{\rm side} = 2^9 = 512$, corresponding to about 47 arcmin^2. The KWFC fields of view are shown in the box and the area observed with Tripole5 is shown in dots. (Color online)

Table 2. Summary of Kiso KWFC observations.

Exposure start time (UT)	Middle time (MJD)	Field	RA	Dec	Filter	$t_{\rm exp}$ (s)	$m_{\rm lim}$ (5σ)
2015-09-18 19:06:02	57283.7969	KT009891	$09^{\rm h}05^{\rm m}35\overset{\rm s}{.}52$	$+10°27'00\overset{''}{.}0$	i	180	19.2
2015-09-18 19:11:37	57283.8008	KT009892	$09^{\rm h}14^{\rm m}32\overset{\rm s}{.}16$	$+10°27'00\overset{''}{.}0$	i	180	18.9
2015-09-18 19:16:59	57283.8045	KT009893	$09^{\rm h}23^{\rm m}28\overset{\rm s}{.}80$	$+10°27'00\overset{''}{.}0$	i	180	18.9
2015-09-18 19:22:22	57283.8083	KT009894	$09^{\rm h}32^{\rm m}25\overset{\rm s}{.}44$	$+10°27'00\overset{''}{.}0$	i	180	18.9
2015-09-18 19:34:29	57283.8167	KT009895	$09^{\rm h}41^{\rm m}22\overset{\rm s}{.}08$	$+10°27'00\overset{''}{.}0$	i	180	16.3

The total probability of the regions observed with KWFC to include the GW source was initially 1.2% but turned out to be 0.1% in the final skymap. These regions are partly overlapped with regions covered by Pan-STARRS (PS1: Smartt et al. 2016) and MASTER-NET (Lipunov et al. 2016).[1]

The data reduction procedure basically follows that of the supernova (SN) survey with KWFC (Morokuma et al. 2014). The $5\,\sigma$ limiting magnitudes are ∼19 mag for the first four images and as shallow as 16.2 mag for the last image due to the twilight. For each of the fully reduced images, we applied an image subtraction method (hotpants)[2] with deeper archival Sloan Digital Sky Survey (SDSS) images taken several years ago as references. Then, we extracted transient objects with positive fluxes ($2.5\,\sigma$, 5 pixel connection) in the subtracted images with SExtractor (Bertin & Arnouts 1996).

2.2 B&C 61 cm Tripole5 observations

Tripole5 is an optical camera on the 61 cm B&C telescope capable of taking images in a $6\overset{\prime}{.}2 \times 4\overset{\prime}{.}2$ field of view in g-, r-, and i-bands, simultaneously.

The observations were started on 2015 September 20, 6.3 days after the GW detection. We observed 18 nearby galaxies in the high probability region of the Southern Hemisphere as shown in figure 1 and table 3. Two to six 120 s frames were taken per galaxy in g-, r-, and i-bands on 2015 September 20, 21, 24, and 26. The observed galaxies were selected from the Gravitational Wave Galaxy Catalogue (GWGC: White et al. 2011) based on the initial skymap and are closer than 100 Mpc so that an EM counterpart of an NS–NS merger could be detected. All the galaxies observed are located within the ∼200 deg^2 of the overlapped localization region (90% confidence) of GW150914 and GW150914-GBM, detected with the Gamma-ray Burst Monitor (GBM) on board the Fermi Gamma-ray Space Telescope (Connaughton et al. 2016).

The total probabilities in the initial and final skymaps are 0.003%, although the distance $d = 410^{+160}_{-180}$ Mpc is farther than the maximum distances to the galaxies by a factor of ∼4. The number of observed galaxies is ∼4% of the galaxies in the GWGC catalog within the 90% probability region.

The data were reduced in a standard manner using IRAF. Zeropoint magnitudes in the g-, r-, and i-bands were determined relative to the B-, R-, and I-band magnitudes of objects in the USNO-B1.0 catalog (Monet et al. 2003) using the conversion equations in Fukugita et al. (1996). Medians of the $5\,\sigma$ limiting magnitudes are $g = 18.9$ mag, $r = 18.7$ mag, and $i = 18.3$ mag. The object catalogs for the Tripole5 images were created using SExtractor.

3 Results and discussion

For the KWFC data, radial profiles and SDSS classifications (star/galaxy separation based on probPSF information available in the SDSS database) of all of the transient objects were used to extract extragalactic transients. Known asteroids were also checked with MPChecker and removed from the transient catalog. For the Tripole5 data, the object catalog in the entire observed field of each target galaxy was first compared with the USNO-B1.0 catalog. There remained some objects without any counterparts in the USNO-B1.0 catalog and they were visually inspected by comparing the Tripole5 images with the Digitized Sky Survey images.

In the procedures described above, we found no extragalactic transient object with a spatial offset from its host galaxy, although we detected variability at the centers of several external galaxies (including PS15cek described below). Given the survey areas, depths of the data, and the measured volumetric SN rates in the local universe (Blanc et al. 2004 for Type Ia SNe; Li et al. 2011 for Core-Collapse SNe), the expected number of SNe is smaller than unity. This is consistent with the result that we do not find any SN candidate.

Among transient objects discovered and reported by other projects so far (PS1 by Smartt et al. 2016; UVOT on the Swift satellite by Evans et al. 2016; La Silla-QUEST by Rabinowitz et al. 2015; iPTF by Singer et al. 2015 and Kasliwal et al. 2016), four transients are within the regions observed with KWFC: PS15cej, PS15cek, PS15ckf,

[1] ⟨http://master.sai.msu.ru/static/G184098/G184098_4.png⟩.

[2] ⟨http://www.astro.washington.edu/users/becker/v2.0/hotpants.html⟩.

Table 3. Summary of B&C 61 cm telescope Tripole5 observations.

Galaxy	RA*	Dec*	d [Mpc]*	Filters	2015-09-20†	2015-09-21†	2015-09-24†	2015-09-26†
ESO034-012	$06^h43^m30^s.8$	$-72°35'41''$	74.22 ± 11.13	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO058-014	$06^h46^m36^s.1$	$-70°36'54''$	93.42 ± 14.01	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO058-023	$07^h04^m45^s.5$	$-71°00'59''$	92.83 ± 13.93	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO059-023	$07^h56^m06^s.1$	$-68°16'41''$	70.51 ± 10.58	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO060-010	$08^h38^m36^s.7$	$-67°56'11''$	96.96 ± 14.54	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO060-011	$08^h42^m43^s.0$	$-67°48'54''$	94.97 ± 14.25	g, r, i	120 × 2	120 × 2	120 × 4	120 × 4
ESO060-018	$08^h56^m40^s.5$	$-67°52'13''$	84.89 ± 12.73	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO089-009	$08^h05^m09^s.0$	$-67°35'12''$	95.29 ± 20.96	g, r, i	120 × 4	120 × 2	120 × 6	120 × 4
ESO089-015	$08^h18^m08^s.1$	$-67°34'37''$	96.53 ± 21.24	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO089-016	$08^h18^m23^s.4$	$-67°36'40''$	97.78 ± 21.51	g, r, i	120 × 2	120 × 2	120 × 4	120 × 4
ESO090-011	$08^h58^m18^s.5$	$-65°22'03''$	72.93 ± 10.94	g, r, i	120 × 2	120 × 2	120 × 4	120 × 4
ESO126-023	$09^h37^m51^s.2$	$-62°09'04''$	33.42 ± 5.01	g, r, i	–	120 × 2	120 × 4	120 × 4
ESO126-024	$09^h38^m29^s.1$	$-61°49'47''$	33.42 ± 5.01	g, r, i	120 × 2	120 × 2	120 × 4	120 × 4
NGC 2150	$05^h55^m46^s.3$	$-69°33'39''$	58.89 ± 8.83	g, r, i	120 × 3	120 × 2	120 × 4	120 × 4
NGC 2187	$06^h03^m48^s.5$	$-69°35'00''$	59.56 ± 8.93	g, r, i	120 × 4	120 × 2	120 × 4	120 × 4
NGC 2187A	$06^h03^m44^s.2$	$-69°35'18''$	50.93 ± 11.21	g, r, i	120 × 2	120 × 2	120 × 4	120 × 4
NGC 2442	$07^h36^m23^s.8$	$-69°31'51''$	17.30 ± 2.60	g, r, i	–	120 × 3	120 × 4	120 × 4
NGC 2466	$07^h45^m16^s.0$	$-71°24'38''$	70.86 ± 10.63	g, r, i	120 × 2	120 × 2	120 × 4	120 × 4

*Coordinates of the center of the galaxy. The distances, d, to the galaxies are derived from the GWGC (White et al. 2011).
†Exposure time on each date for each galaxy in seconds.

Table 4. Transients reported in other papers in our survey fields.

Name	RA	Dec	Reference	Nature	Discovery*	ID*	Explosion*	J-GEM	Note
PS15cej	$09^h35^m19^s.41$	$+10°11'50''.7$	Smartt et al. (2016)	SN Ia	2015-10-02	2015-10-10	2015-09-22	KWFC	Before expl.
PS15cek	$09^h36^m41^s.04$	$+10°14'16''.2$	Smartt et al. (2016)	AGN	2015-10-02	–	–	KWFC	–
PS15ckf	$09^h45^m57^s.71$	$+09°58'31''.4$	Smartt et al. (2016)	SN II	2015-10-03	2015-10-20	2015-09-27	KWFC	Before expl.
PS15dft	$09^h33^m09^s.38$	$+10°28'02''.2$	Smartt et al. (2016)	CV	2015-10-23	–	–	KWFC	–

*Dates of discovery, PS1 spectroscopic identification, and explosion based on the spectroscopic phase.

and PS15dft (table 4). All these PS1 transients were discovered early October in 2015, while our KWFC data were taken in 2015 September. PS15cek is a known AGN (2MFGC 07447: Véron-Cetty & Véron 2001) at $z = 0.060$, and its variability is also detected in our KWFC images compared with the past SDSS data. We do not detect variabilities of the other three objects, i.e., two SNe (PS15cej, PS15ckf) and one cataclysmic variable star (PS15dft or ASASSN-15se), but the non-detection of variability is not surprising since these explosions and flare are likely to occur after our observations in September (Smartt et al. 2016).

Several theoretical scenarios for EM counterparts of BH–BH mergers and their emissions are available. Nakamura, Nakano, and Tanaka (2016) calculated an expected optical emission from almost the same system as GW150914. In their model, the Eddington luminosity of a $60\,M_{\odot}$ BH in dense interstellar medium may have a brightness of about 26 mag if the emission is radiated mainly in the optical wavelength at a similar distance to GW150914 ($d \sim$ 300 Mpc), which can be detected with 8 m class telescopes and instruments. Yamazaki, Asano, and Ohira (2016) and Morsony, Workman, and Ryan (2016) predict a wide range of EM emissions from GW150914 under the assumption that GW150914-GBM (Connaughton et al. 2016) is associated with GW150914 (Loeb 2016). They suggest that an optical counterpart is detectable with 8 m class telescopes within one or a few days after the GW event, and that earlier emission within several hours after the event can be detected with smaller aperture (2–4 m) telescopes.

These theoretical models indicate that wide-field surveys with 8 m class telescopes and instruments such as Subaru HSC or the Large Synoptic Survey Telescope (LSST: LSST Science Collaboration 2009) are the best strategy to detect an optical counterpart of a GW event like GW150914. If a similar event to GW150914 occurs at a closer distance, an optical counterpart could be detectable with 1–2 m class telescopes. Although selecting the counterpart from a huge amount of imaging data is challenging, several intensive studies have been done. Implementations of machine-learning techniques for reducing real-to-bogus ratios with wide-field imaging data have been undertaken in several projects (e.g., Bloom et al. 2012; Brink et al. 2013). Among the J-GEM instruments, a machine-learning approach for effective discoveries of transient objects is being taken for Subaru HSC data (Morii et al. 2016). Effective classification trials for many transient objects (Kessler et al. 2010) by adding realistic theoretical models for GW EM counterparts including NS–NS merger (see the review by Tanaka 2016) will also help us to identify the EM counterpart in the near future.

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