

Subaru Hyper Suprime-Cam Survey for an optical counterpart of GW170817[†]

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Abstract

We perform a z-band survey for an optical counterpart of the binary neutron star coalescence GW170817 with Subaru/Hyper Suprime-Cam. Our untargeted transient search covers 23.6 deg^2 corresponding to the 56.6% credible region of GW170817 and reaches the 50% completeness magnitude of 20.6 mag on average. As a result, we find 60 candidate extragalactic transients, including J-GEM17btc (also known as SSS17a/DLT17ck). While J-GEM17btc is associated with NGC 4993, which is firmly located inside the 3D skymap of GW170817, the other 59 candidates do not have distance information in the GLADE v2 catalog or NASA/IPAC Extragalactic Database. Among 59 of the candidates, 58 are located at the center of extended objects in the Pan-STARRS1 catalog, while one candidate has an offset. We present location, z-band apparent magnitude, and time variability of the candidates and evaluate the probabilities that they are located within the 3D skymap of GW170817. The probability for J-GEM17btc is 64%, which is much higher than for the other 59 candidates (9.3×10^{-3} – $2.1 \times 10^{-1}\%$). Furthermore, the possibility that at least one of the other 59 candidates is located within the 3D skymap is only 3.2%. Therefore, we conclude that J-GEM17btc is the most likely and distinguished candidate to be the optical counterpart of GW170817.

Key words: gravitational waves — nuclear reactions, nucleosynthesis, abundances — stars: neutron — surveys

1 Introduction

The existence of gravitational waves (GWs) is predicted in the theory of general relativity. Although the existence is indirectly demonstrated by the energy loss of a binary pulsar system (Hulse & Taylor 1975; Taylor & Weisberg 1982), the direct observation of GWs had not been realized owing to their small amplitudes. The first direct detection is achieved with the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) on 2015 September 14 (Abbott et al. 2016a). The first GW source originates from the coalescence of two black holes, each $\sim 30 M_{\odot}$. The discovery is important not only as a direct probe of the strong field dynamics of general relativity, but also as the first evidence of a black hole binary. LIGO and Advanced Virgo subsequently detect three GW signals and one candidate signal, all from the coalescence of black hole binaries (Abbott et al. 2016b, 2016c, 2017b, 2017c). These discoveries open the era of “gravitational wave astronomy.”

However, the conclusive identification of the GW sources on the sky remains challenging because of the poor sky localization with the gravitational wave observations. The sky localization areas of four GW sources are about 230 – 1160 deg^2 (90% credible region) with two detectors of LIGO and about 60 deg^2 (90% credible region) even with three detectors including the Advanced Virgo. Since there are many galaxies in the area, it is impossible to determine the host galaxy of a GW source only with the GW observations. Therefore, multi-wavelength searches for electromagnetic (EM) counterparts are initiated after the alerts of GW detection from the LIGO-Virgo networks. So far, no firm EM counterparts have been found (e.g., Soares-Santos et al. 2016; Smartt et al. 2016; Kasliwal et al. 2016; Morokuma et al. 2016; Yoshida et al. 2017), except for a report of the putative detection of GW150914 with Fermi/GBM (Connaughton et al. 2016, which is however questioned by Savchenko et al. 2016; Greiner et al. 2016).

The non-detection of EM counterparts is not surprising because the four GWs originate from mergers of black holes, although several theoretical studies try to explain the putative Fermi/GBM emission (e.g., Yamazaki et al. 2016). On the other hand, first-principle numerical simulations with general relativity demonstrate that binary coalescence including at least one neutron star (NS) can eject materials as dynamical ejecta (e.g., Rosswog et al. 1999; Goriely et al. 2011; Hotokezaka et al. 2013; Bauswein et al. 2013) and post-merger ejecta (e.g., Dessart et al. 2009; Fernández & Metzger 2013; Shibata et al. 2017). The ejecta dominantly consist of r -process elements (e.g., Lattimer & Schramm 1974; Eichler et al. 1989; Korobkin et al. 2012; Wanajo et al. 2014), and thus the decay of radioactive isotopes produced by the r -process nucleosynthesis heats up and brightens the ejecta. The EM-bright object is called a “kilonova” or “macronova” (Li & Paczyński 1998; Kulkarni 2005; Metzger et al. 2010), and is regarded as a promising EM counterpart of a GW (Metzger & Berger 2012; Kasen et al. 2013, 2015; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013; Metzger & Fernández 2014; Tanaka et al. 2014; Metzger 2017). Also, the central engine of a short gamma-ray burst, which is believed to originate from a binary neutron star coalescence, is a possible energy source of EM counterparts through its jet and gamma/X-ray emission (e.g., Kisaka et al. 2016).

On 2017 August 17, 12:41:04 UTC, Advanced LIGO and Advanced Virgo detected a GW candidate from a binary NS coalescence; this was coincident with a gamma-ray detection with Fermi/GBM (The LIGO Scientific Collaboration & the Virgo Collaboration 2017a, 2017b). The sky localization with the three detectors is as narrow as 28 deg^2 for a 90% credible region centered at RA = $13^{\text{h}}08^{\text{m}}$, Dec = $-22^{\circ}30'$ (J2000.0) (Abbott et al. 2017d). In addition, the localization is overlapped with the error regions of gamma-ray detection with Fermi/GBM and INTEGRAL (Connaughton et al. 2017; Savchenko et al. 2017a, 2017b). The GW observation reveals the luminosity distance to the GW source, named GW170817, as $40^{+8}_{-14} \text{ Mpc}$ (90% probability) (Abbott et al. 2017d). Although GW170817 appeared at a position close to the Sun, the first significant alert of a binary NS coalescence and the narrow sky localization area initiated many EM follow-up observations (Abbott et al. 2017a).

Along with the EM follow-up observation campaign of GW170817, the Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM) performed a survey with Hyper Suprime-Cam (HSC: Miyazaki et al. 2012), which is a wide-field imager installed on the prime focus of the 8.2 m Subaru telescope. Its field of view (FoV) of 1.77 deg^2 is largest among the currently existing 8–10 m telescopes, and thus it is the most efficient instrument for the

Table 1. Subaru/HSC pointings.

Pointing (ID)	RA (J2000.0)	Dec (J2000.0)
04	$13^{\text{h}}07^{\text{m}}25^{\text{s}}$	$-26^{\circ}36'51''$
05	$13^{\text{h}}10^{\text{m}}14^{\text{s}}$	$-27^{\circ}17'02''$
06	$13^{\text{h}}13^{\text{m}}03^{\text{s}}$	$-27^{\circ}57'27''$
07	$13^{\text{h}}15^{\text{m}}51^{\text{s}}$	$-28^{\circ}38'07''$
08	$13^{\text{h}}18^{\text{m}}40^{\text{s}}$	$-29^{\circ}19'02''$
09	$13^{\text{h}}21^{\text{m}}29^{\text{s}}$	$-30^{\circ}00'15''$
10	$13^{\text{h}}04^{\text{m}}36^{\text{s}}$	$-24^{\circ}37'42''$
11	$13^{\text{h}}07^{\text{m}}25^{\text{s}}$	$-25^{\circ}17'12''$
12	$13^{\text{h}}10^{\text{m}}14^{\text{s}}$	$-25^{\circ}56'55''$
13	$13^{\text{h}}13^{\text{m}}03^{\text{s}}$	$-26^{\circ}36'51''$
14	$13^{\text{h}}01^{\text{m}}48^{\text{s}}$	$-22^{\circ}40'26''$
15	$13^{\text{h}}15^{\text{m}}51^{\text{s}}$	$-27^{\circ}17'02''$
16	$13^{\text{h}}18^{\text{m}}40^{\text{s}}$	$-27^{\circ}57'27''$
17	$13^{\text{h}}04^{\text{m}}36^{\text{s}}$	$-23^{\circ}19'20''$
18	$13^{\text{h}}07^{\text{m}}25^{\text{s}}$	$-23^{\circ}58'25''$
19	$12^{\text{h}}58^{\text{m}}59^{\text{s}}$	$-20^{\circ}44'47''$
20	$13^{\text{h}}10^{\text{m}}14^{\text{s}}$	$-24^{\circ}37'43''$
22	$13^{\text{h}}13^{\text{m}}03^{\text{s}}$	$-25^{\circ}17'12''$
23	$13^{\text{h}}15^{\text{m}}51^{\text{s}}$	$-25^{\circ}56'55''$
24	$12^{\text{h}}56^{\text{m}}10^{\text{s}}$	$-18^{\circ}50'37''$
25	$13^{\text{h}}04^{\text{m}}36^{\text{s}}$	$-22^{\circ}01'43''$
26	$13^{\text{h}}07^{\text{m}}25^{\text{s}}$	$-22^{\circ}40'26''$
28	$13^{\text{h}}10^{\text{m}}14^{\text{s}}$	$-23^{\circ}19'20''$
29	$13^{\text{h}}01^{\text{m}}48^{\text{s}}$	$-20^{\circ}06'35''$

optical survey. In this paper, we summarize the observation with Subaru/HSC and properties of discovered candidates. Throughout the paper, we correct the Galactic reddening (Schlafly & Finkbeiner 2011),¹ and all the magnitudes are given as AB magnitudes.

2 Observation and data analysis

We started HSC observation on 2017 August 18.23 (UTC), corresponding to 0.7 d after the GW detection, and also performed HSC observation on August 19, 25, and 27. All the observations were carried out in the z -band. The poor visibility of GW170817 from Mauna Kea compelled us to conduct the survey during the astronomical twilight. The observations on August 25 and 27 were concentrated on one field because the target fields set immediately after sunset. The survey pointings are selected from a HEALPix grid with resolution of NSIDE = 64 using the following criteria: higher probability of GW170817 sky localization and larger number of nearby galaxies in the GLADE catalog (Daly et al. 2016; table 1).² We also choose the pointings located in footprints of Pan-STARRS1 (PS1, Chambers et al. 2016) and use the PS1 catalog and images for astrometric calibration and image subtraction, respectively. The

¹ (<http://irsa.ipac.caltech.edu/applications/DUST/>).

² (<http://aquarius.elte.hu/glade/index.html>).

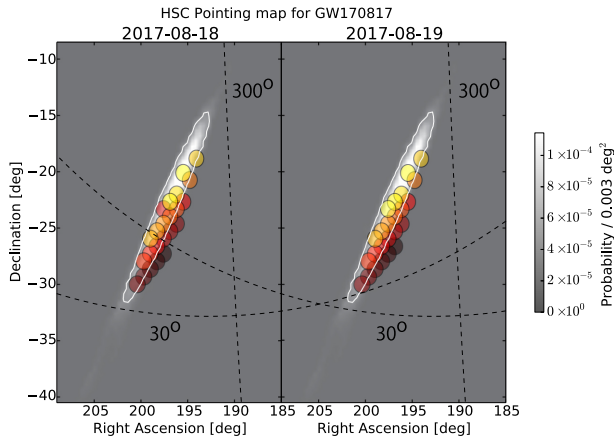


Fig. 1. Pointing map for GW170817 overlaid on the probability map³ (Abbott et al. 2017d). The white contour represents the 90% credible region. Circles represent the field-of-view of HSC; their colors changing with an order of observation. Observations have been carried out from darker to lighter colors. The dashed curves represent the Galactic graticules. (Color online)

observed area is 28.9 deg^2 corresponding to the 66.0% credible region of GW170817 (figure 1). Exposures used in the following analysis are listed in table 2.

The data are analyzed with HSCPIPE v4.0.5, which is a standard reduction pipeline of HSC (Bosch et al. 2018). It provides full packages for data analyses of images obtained with HSC, including bias subtraction, flat-fielding, astrometry, flux calibration, mosaicing, warping, stacking, image subtraction, source detection, and source measurement. The astrometric and photometric calibration is made relative to the PS1 catalog with a $4''.0$ (24 pixel) aperture diameter. Further, in order to select variable sources, we perform image subtraction between the HSC and archival PS1 z -band images using a package in HSCPIPE based on an algorithm proposed by Alard and Lupton (1998). The PS1 images are adopted as the reference images and convolved to fit the point spread function (PSF) shape of the HSC images.

We measure the FWHM sizes of PSF in the stacked images with HSCPIPE. These scatter over a wide range from $0''.7$ to $1''.8$ depending on the pointings, especially on the elevation, and the median is $\sim 1''.2$ (figure 2). The PSF size statistics are summarized in table 3. The median FWHM size is slightly worse than that of the image quality of the PS1 3π survey (Magnier et al. 2016a), and the PSF convolution of the PS1 image for the image subtraction works well.

After the image subtraction, the 5σ limiting magnitudes in the difference images are estimated by measuring standard deviations of fluxes in randomly distributed apertures

with a diameter of twice the FWHM of PSF, and scatter from 18.3 mag to 22.5 mag with a median of 21.3 mag (figure 3 and table 4). The 5σ limiting magnitudes are mainly determined by the depths of HSC images, which are typically shallower than those of the PS1 image. In particular, the depths in the pointings observed early on August 19 are quite shallow. We also evaluate completeness of detection by a random injection and detection of artificial point sources with various magnitude (dashed lines in figure 4). The magnitude of artificial point sources are fixed in time. The large diversity in the depth of images taken on August 19 causes the shallow dependence of completeness on the PSF magnitude of artificial sources. The median of 5σ limiting magnitude is roughly comparable to the 70% completeness magnitude.

As the detected sources include many bogus detections, candidate selection is performed as in Utsumi et al. (2018). Criteria for the detection in a single difference image are (1) $|(S/N)_{\text{PSF}}| > 5$, (2) $(b/a)/(b/a)_{\text{PSF}} > 0.65$, where a and b are the lengths of the major and minor axes of a shape of a source, respectively, (3) $0.7 < \text{FWHM}/(\text{FWHM})_{\text{PSF}} < 1.3$, and (4) PSF-subtracted residual $< 3\sigma$. These criteria confirm a high confidence level of detection and the stellar-like shape of a source. Further, we impose the sources to be detected in both of the difference images on August 18 and 19, and find 1551 sources. We also evaluate the completeness of this candidate selection with the artificial point sources (solid lines in figure 4). The candidate selection makes the 50% completeness magnitudes shallower by 0.7–0.8 mag. The completeness of the two-epoch detection is comparable to that seen on August 19 because the observation from August 19 is shallower than that from August 18. The 50% completeness magnitude for two-epoch detection is 20.6 mag.

The two-epoch detection is only possible for the fields with the archival PS1 images and the HSC images on both of August 18 and 19. The resultant area for the transient search is 23.6 deg^2 , corresponding to the 56.6% credible region of GW170817.

3 Transient search and characteristics

3.1 Source screening

As the 1551 sources include sources unrelated to GW170817, we need to screen them in order to pick up candidates that may be related to GW170817. We adopt a procedure shown here in a flowchart (figure 5).

First of all, the flux of optical counterpart of GW170817 needs to not be negative on August 18 and 19. We exclude sources having significantly negative fluxes ($< -3\sigma$) on August 18 or 19. We also rule out sources associated with stellar-like objects in the PS1 catalog (Magnier et al. 2016b;

³ Publication LALInference localization (https://dcc.ligo.org/public/0146/G1701985/001/LALInference_v2.fits.gz).

Table 2. Subaru/HSC observation log of exposures used in the analysis.

Pointing	TaiObs (UTC)	Exposure time (s)	Pointing	TaiObs (UTC)	Exposure time (s)
28	2017-08-18T05:30:27	20.0	14	2017-08-19T05:32:51	30.0
05	2017-08-18T05:32:00	30.0	15	2017-08-19T05:33:54	30.0
06	2017-08-18T05:33:01	30.0	16	2017-08-19T05:34:55	30.0
07	2017-08-18T05:34:03	30.0	17	2017-08-19T05:35:59	30.0
08	2017-08-18T05:35:03	30.0	18	2017-08-19T05:37:01	30.0
09	2017-08-18T05:36:03	30.0	19	2017-08-19T05:38:02	30.0
10	2017-08-18T05:37:10	30.0	20	2017-08-19T05:39:03	30.0
11	2017-08-18T05:38:10	30.0	22	2017-08-19T05:40:05	30.0
12	2017-08-18T05:39:10	30.0	23	2017-08-19T05:41:06	30.0
28	2017-08-18T05:40:11	60.0	24	2017-08-19T05:42:15	30.0
13	2017-08-18T05:41:41	30.0	25	2017-08-19T05:43:15	30.0
14	2017-08-18T05:42:42	30.0	26	2017-08-19T05:44:15	30.0
15	2017-08-18T05:43:45	30.0	29	2017-08-19T05:45:16	30.0
16	2017-08-18T05:44:46	30.0	28	2017-08-19T05:46:17	30.0
17	2017-08-18T05:45:50	30.0			
18	2017-08-18T05:46:51	30.0	28	2017-08-25T05:22:45	10.0
19	2017-08-18T05:47:52	30.0	28	2017-08-25T05:23:26	10.0
20	2017-08-18T05:48:54	30.0	28	2017-08-25T05:24:06	10.0
22	2017-08-18T05:49:55	30.0	28	2017-08-25T05:24:48	10.0
23	2017-08-18T05:50:55	30.0	28	2017-08-25T05:25:29	20.0
24	2017-08-18T05:52:05	30.0	28	2017-08-25T05:27:10	20.0
25	2017-08-18T05:53:09	30.0	28	2017-08-25T05:28:01	30.0
26	2017-08-18T05:54:11	30.0	28	2017-08-25T05:29:07	30.0
29	2017-08-18T05:55:16	30.0			
			28	2017-08-27T05:24:07	10.0
04	2017-08-19T05:22:21	10.0	28	2017-08-27T05:24:48	10.0
05	2017-08-19T05:23:02	10.0	28	2017-08-27T05:25:28	10.0
06	2017-08-19T05:23:46	10.0	28	2017-08-27T05:26:09	10.0
07	2017-08-19T05:24:29	10.0	28	2017-08-27T05:26:49	10.0
08	2017-08-19T05:25:11	10.0	28	2017-08-27T05:27:30	10.0
09	2017-08-19T05:25:57	10.0	28	2017-08-27T05:28:10	10.0
28	2017-08-19T05:26:44	30.0	28	2017-08-27T05:28:51	10.0
10	2017-08-19T05:27:44	30.0	28	2017-08-27T05:29:32	10.0
11	2017-08-19T05:28:45	30.0	28	2017-08-27T05:30:12	10.0
12	2017-08-19T05:29:47	30.0	28	2017-08-27T05:30:53	10.0
13	2017-08-19T05:30:49	30.0	28	2017-08-27T05:31:34	10.0
28	2017-08-19T05:31:49	30.0	28	2017-08-27T05:32:15	20.0

Flewelling et al. 2016) with a separation of $<1''.4$.⁴ Here we adopt a larger separation, similar to the typical seeing size, than the astrometric error in order to remove bogus detection that frequently appears around a bright star. According to the number density of stellar-like objects in the PS1 catalog, this exclusion reduces only 0.2% of the survey fields. After this screening, 384 sources remain. While 322 sources are located at the center of extended objects in the PS1 catalog, 62 sources have separations of $>1''$ to any objects in the PS1 catalog.

We further exclude sources associated with PS1 objects that are firmly located outside of the 3D skymap (see

footnote 3) derived from the GW observations (Abbott et al. 2017d), adopting the GLADE v2 catalog and NASA/IPAC Extragalactic Database (NED).⁵ While we primarily employ the distance in the GLADE catalog, we replace it with the redshift-independent distance in NED if the associated PS1 objects or one of a galaxy pair containing the associated PS1 objects have information (Tully 1988; Willick et al. 1997; Freedman et al. 2001; Theureau et al. 2007; Sorce et al. 2014; Springob et al. 2014), and with the redshift-dependent distance in NED (Mould et al. 2000) if no distance information is available in the GLADE catalog. We

⁴ (<https://panstarrs.stsci.edu/>).

⁵ The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (<https://ned.ipac.caltech.edu/>).

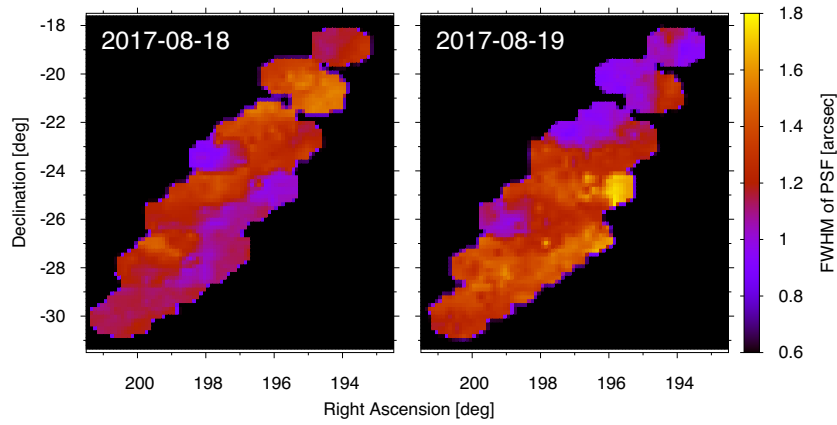


Fig. 2. Map of FWHM of PSF in the stacked images on 2017 August 18 and 19. (Color online)

Table 3. Seeing of stacked images.

Date (UTC)	FWHM of PSF (")		
	Min.	Median	Max.
2017-08-18	0.91	1.20	1.62
2017-08-19	0.73	1.25	1.80
2017-08-25	0.75	0.90	1.16
2017-08-27	1.13	1.21	1.50

Table 4. 5σ limiting magnitude of difference images.

Date (UTC)	Limiting magnitude (mag)		
	Min	Median	Max
2017-08-18	20.47	21.61	22.51
2017-08-19	18.30	20.97	22.21
2017-08-25	21.06	21.50	21.74
2017-08-27	20.36	20.75	21.00

search for possibly associated galaxies in the GLADE catalog or NED with a separation of $<2''.0$ for the 322 sources at the center of extended PS1 objects, which is smaller than the criteria used when identifying duplicate galaxies in the GLADE catalog ($3''.6$), and with a separation of $<15''.0$ for the 62 off-center sources, which corresponds to a separation of <3 kpc at a distance of 40 Mpc. If the 3D probability of GW170817 occurrence at the location and distance of the associated PS1 object with a HEALPix 3D grid with resolution of $\text{NSIDE} = 1024$ is less than 10^{-3} of the maximum probability, the source is ruled out. This screening reduces the number of sources to 224 sources

at the center of extended PS1 objects and 59 off-center sources.

There is only one source (J-GEM17btc) associated with a PS1 object that is located in the 3D skymap. J-GEM17btc is described in more detail in the next subsection. In contrast, the remaining 282 sources do not have distance measurements in the GLADE catalog or in NED. After the catalog matching, four of the authors removed bogus and high proper motion stars by visual inspection (figure 6). The number of final candidates, which may be related to GW170817, is 60 (table 5). We note that 58 candidates are located at the center of extended PS1 objects and that

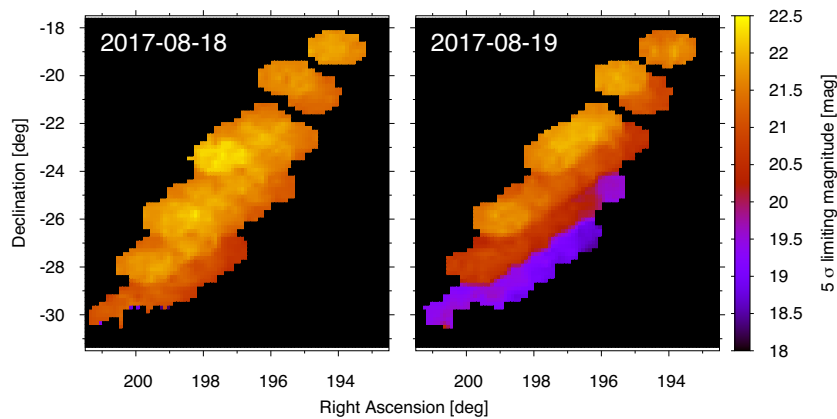


Fig. 3. Map of 5σ limiting magnitude in the difference images on 2017 August 18 and 19. (Color online)

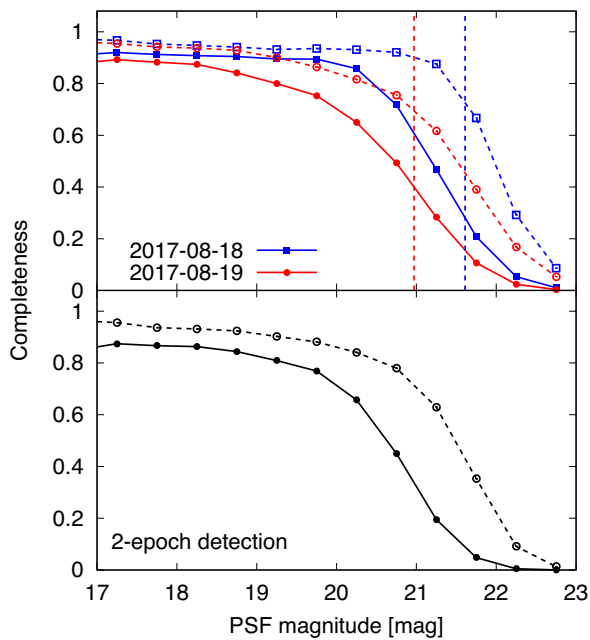


Fig. 4. Completeness of transient detection in the difference images on August 18 (squares) and August 19 (circles) (top) and in both of the difference images (bottom). The dashed and solid lines represent completeness before and after the candidate selection, respectively. The vertical dashed lines show the median of the 5σ limiting magnitude before the candidate selection. (Color online)

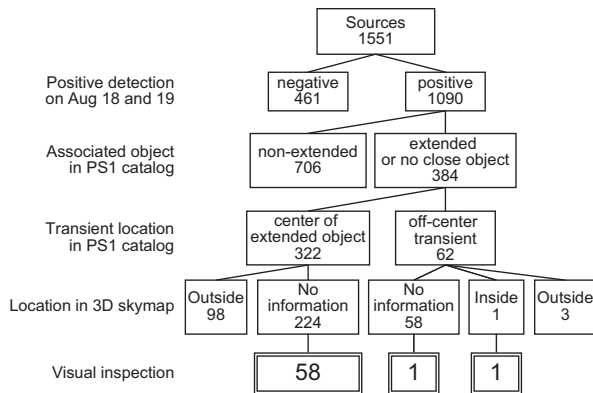


Fig. 5. Flowchart of the candidate screening process. The number in each box represents the number of sources remaining after each screening.

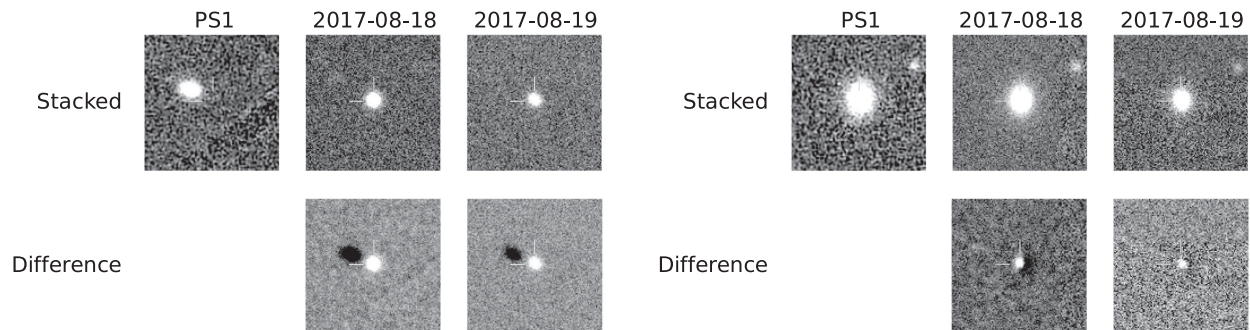


Fig. 6. Example of sources excluded by the visual inspection: (top) high proper motion stars and (bottom) bogus detection at the center of the extended objects. The length of the ticks is $2''$ and the figure size is $20 \times 20 \text{ arcsec}^2$.

some of them could be active galactic nuclei (AGN) or indistinguishable residuals resulting from different instrumental signatures between PS1 and HSC, but we conservatively consider them as candidates.

3.2 Properties of candidates

We investigate the properties of the remaining 60 candidates.

Figure 7 shows the candidate with the associated PS1 object within the 3D skymap of GW170817. J-GEM17btc is located at $\text{RA} = 13^{\text{h}}09^{\text{m}}48^{\text{s}}.07$, $\text{Dec} = -23^{\circ}22'53''.4$ (J2000.0), which is SSS17a/DLT17ck reported by Coulter et al. (2017a, 2017b) and Valenti et al. (2017). The nearest object in the PS1 catalog is PSO J130947.744–232257.366 at $\text{RA} = 13^{\text{h}}09^{\text{m}}47^{\text{s}}.74$, $\text{Dec} = -23^{\circ}22'57''.4$ (J2000.0) with a separation of $6''.0$ to J-GEM17btc, which is superposed on NGC 4993 and located at $4''.6$ north of the center of NGC 4993. According to an archival Hubble Space Telescope (HST) ACS image (Bellini et al. 2017), the PSF shape of PSO J130947.744–232257.366 is consistent with stellar-like sources surrounding it and PSO J130947.744–232257.366 is unlikely to be relevant to J-GEM17btc. Thus, we conclude that the second-closest object, NGC 4993, located $10''.0$ away from J-GEM17btc (well within the separation criterion of $15''.0$) is associated with J-GEM17btc. NGC 4993 is an S0 galaxy at the distance of $\sim 40 \text{ Mpc}$ (Freedman et al. 2001).

Among remaining 59 candidates, one candidate (J-GEM17bog) at $\text{RA} = 13^{\text{h}}04^{\text{m}}44^{\text{s}}.11$, $\text{Dec} = -22^{\circ}37'07''.2$ (J2000.0) is registered as an off-center transient (figure 8). However, we marginally find a persistent object overlapping with a galaxy in the archival PS1 *i*-band image, which is not registered in the PS1 catalog. The other 58 candidates are located at the center of extended PS1 objects. Among them, two candidates are associated with X-ray sources in the ROSAT catalog (Boller et al. 2016) with separations

Table 5. 60 final candidates.*

Name	RA (J2000.0)	Dec (J2000.0)	Name	RA (J2000.0)	Dec (J2000.0)
Off-center candidates			J-GEM17bsm	13 ^h 10 ^m 51 ^s .41	−23°10′50″.3
J-GEM17bog	13 ^h 04 ^m 44 ^s .11	−22°37′07″.2	J-GEM17bsn	13 ^h 10 ^m 24 ^s .42	−23°09′35″.7
J-GEM17btc	13 ^h 09 ^m 48 ^s .07	−23°22′53″.4	J-GEM17bti	13 ^h 09 ^m 41 ^s .65	−23°16′04″.4
Candidates at the center of extended objects			J-GEM17bvu	13 ^h 08 ^m 02 ^s .66	−23°25′52″.0
J-GEM17adx	13 ^h 17 ^m 42 ^s .18	−27°49′20″.7	J-GEM17bv	13 ^h 08 ^m 25 ^s .91	−23°25′10″.2
J-GEM17aiu	13 ^h 21 ^m 26 ^s .97	−27°38′13″.5	J-GEM17bv	13 ^h 08 ^m 30 ^s .96	−23°22′46″.7
J-GEM17aoh	13 ^h 18 ^m 25 ^s .05	−25°34′35″.1	J-GEM17byn	13 ^h 02 ^m 23 ^s .21	−20°50′55″.8
J-GEM17aop	13 ^h 17 ^m 12 ^s .45	−26°35′21″.5	J-GEM17bzt	12 ^h 58 ^m 43 ^s .75	−21°12′45″.5
J-GEM17apm	13 ^h 16 ^m 07 ^s .29	−26°00′13″.8	J-GEM17cao	13 ^h 09 ^m 44 ^s .22	−22°08′23″.6
J-GEM17aqg	13 ^h 15 ^m 37 ^s .92	−26°08′51″.4	J-GEM17cch	13 ^h 04 ^m 19 ^s .39	−21°40′18″.4
J-GEM17aqh	13 ^h 15 ^m 32 ^s .63	−25°59′03″.2	J-GEM17cea	12 ^h 54 ^m 39 ^s .55	−19°20′55″.9
J-GEM17aql	13 ^h 15 ^m 33 ^s .44	−25°43′25″.4	J-GEM17ceh	13 ^h 03 ^m 08 ^s .26	−19°44′17″.1
J-GEM17auc	13 ^h 12 ^m 56 ^s .78	−25°53′12″.4	J-GEM17ceo	13 ^h 01 ^m 48 ^s .07	−20°33′48″.3
J-GEM17avc	13 ^h 11 ^m 55 ^s .08	−25°33′48″.2	J-GEM17cet	13 ^h 01 ^m 58 ^s .68	−19°28′36″.2
J-GEM17aws	13 ^h 08 ^m 15 ^s .94	−24°05′35″.3	J-GEM17cfe	13 ^h 01 ^m 15 ^s .18	−19°50′35″.4
J-GEM17axt	13 ^h 07 ^m 31 ^s .91	−24°04′21″.9	J-GEM17cfi	13 ^h 01 ^m 07 ^s .91	−19°29′00″.7
J-GEM17azj	13 ^h 04 ^m 20 ^s .97	−24°05′18″.4	J-GEM17cfm	13 ^h 00 ^m 44 ^s .29	−20°34′49″.4
J-GEM17azl	13 ^h 04 ^m 26 ^s .30	−24°04′19″.2	J-GEM17cfy	12 ^h 59 ^m 29 ^s .55	−20°52′43″.2
J-GEM17bco	13 ^h 12 ^m 14 ^s .45	−24°16′53″.7	J-GEM17cgi	12 ^h 59 ^m 43 ^s .16	−19°32′51″.9
J-GEM17bek	13 ^h 10 ^m 08 ^s .05	−23°58′15″.6	J-GEM17cgq	12 ^h 59 ^m 03 ^s .38	−20°00′20″.9
J-GEM17bfi	13 ^h 09 ^m 53 ^s .68	−23°49′30″.1	J-GEM17cgv	12 ^h 57 ^m 47 ^s .33	−20°34′09″.6
J-GEM17bfs	13 ^h 08 ^m 41 ^s .16	−24°38′41″.9	J-GEM17cio	12 ^h 56 ^m 22 ^s .01	−19°22′38″.3
J-GEM17bgk	13 ^h 08 ^m 37 ^s .03	−23°57′57″.1	J-GEM17ciw	12 ^h 55 ^m 49 ^s .13	−18°49′01″.0
J-GEM17bjh	13 ^h 00 ^m 16 ^s .29	−22°43′30″.2	J-GEM17ciy	12 ^h 55 ^m 45 ^s .53	−18°33′42″.5
J-GEM17bka	13 ^h 07 ^m 47 ^s .41	−23°34′49″.3	J-GEM17cjm	12 ^h 55 ^m 35 ^s .31	−18°20′19″.5
J-GEM17ble	13 ^h 07 ^m 22 ^s .90	−22°19′41″.9	J-GEM17ckf	12 ^h 54 ^m 21 ^s .62	−18°59′05″.8
J-GEM17blv	13 ^h 06 ^m 19 ^s .03	−23°01′44″.5	J-GEM17ckt	13 ^h 01 ^m 47 ^s .22	−19°22′23″.7
J-GEM17bna	13 ^h 05 ^m 31 ^s .84	−22°37′31″.5	J-GEM17ckv	12 ^h 58 ^m 59 ^s .95	−19°11′28″.9
J-GEM17bnb	13 ^h 06 ^m 12 ^s .02	−22°36′51″.6	J-GEM17cld	12 ^h 58 ^m 17 ^s .32	−18°39′20″.4
J-GEM17bsc	13 ^h 11 ^m 55 ^s .67	−23°40′02″.1	J-GEM17clo	12 ^h 57 ^m 59 ^s .20	−19°11′33″.0
J-GEM17bsf	13 ^h 11 ^m 21 ^s .40	−22°44′51″.5	J-GEM17clp	12 ^h 57 ^m 56 ^s .99	−19°11′14″.6

*Some of the candidates at the center of the extended objects could be AGN or indistinguishable residuals resulting from different instrumental signatures between PS1 and HSC.

of 15″.6 and 16″.2, and two other candidates are associated with radio sources in the NRAO VLA Sky Survey (NVSS, 1.4 GHz) catalog (Condon et al. 1998) with separations of 0″.9 and 3″.0. These four candidates could be AGN showing optical variability. We also check the 3XMM-DR7 catalog (Rosen et al. 2016) but there are no associated sources in the 3XMM-DR7 catalog. Although some of them might have little possibility of the association with GW170817, we cannot exclude them as candidates of the optical counterpart of GW170817.

The apparent magnitude on August 18 and time variability between August 18 and 19 of the 60 candidates are shown in figure 9. It is remarkable that J-GEM17btc is much brighter than the other candidates, with ∼19–22 mag. Although this diagram illustrates the distinguished feature of J-GEM17btc, this fact alone is not

conclusive evidence that J-GEM17btc is the most likely counterpart of GW170817.

For comparison, theoretical models of kilonovae at 1–5 d after the merger are also plotted in figure 9 (Tanaka et al. 2014, 2017). Although the observation takes place 1 d after the merger, we adopt a wide range of time after the merger in order to take into account theoretical uncertainties. Although the rapid time evolution is believed to be a clue for identification of a kilonova, the time variability at early epochs of the theoretical models can take any values between −1.0 and +1.0 mag d^{−1}, which is consistent with the properties of all the candidates. On the other hand, there is a discrepancy in the apparent magnitude. However, it can be explained by different ejecta masses, which could result from uncertainties of the equation of state and different efficiency of viscous heating (e.g., Shibata

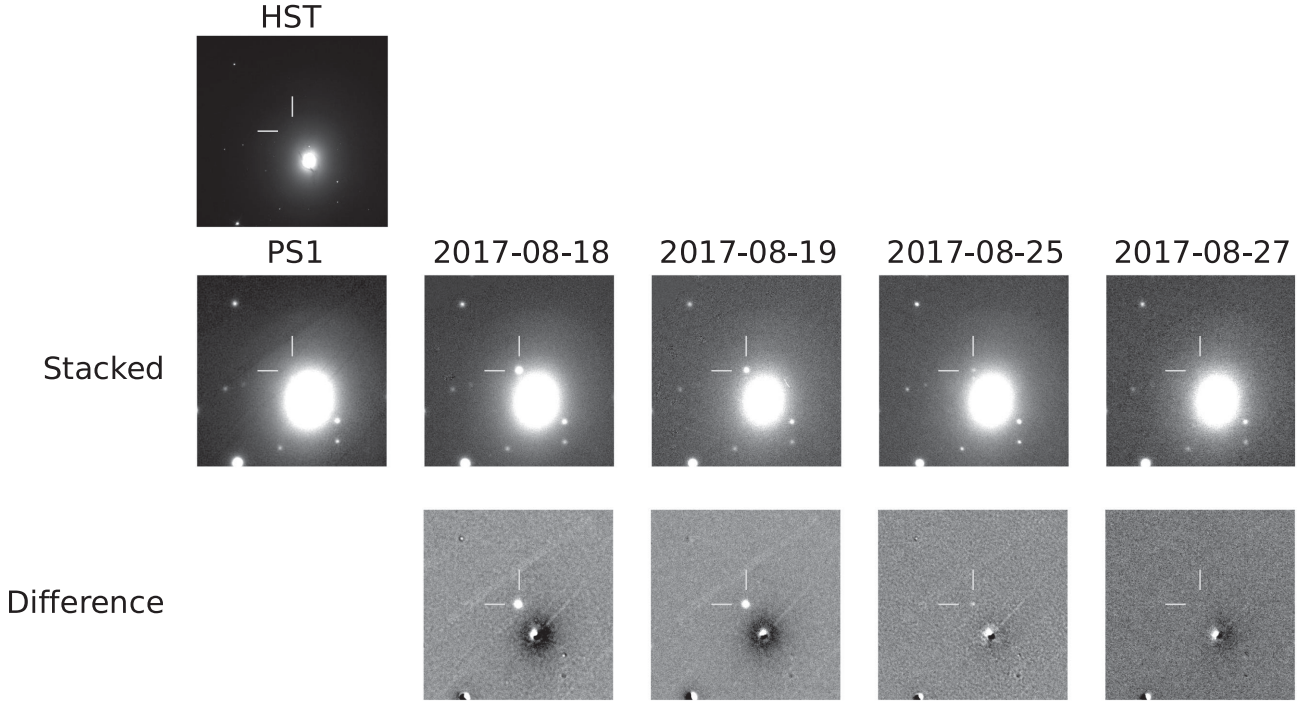


Fig. 7. Stacked and difference z-band images of J-GEM17btc (a.k.a. SSS17a/DLT17ck) associated with NGC 4993 located in the 3D skymap of GW170817. The archival HST ACS image is also shown. The length of the ticks is $11''$ and the figure size is $56 \times 56 \text{ arcsec}^2$.

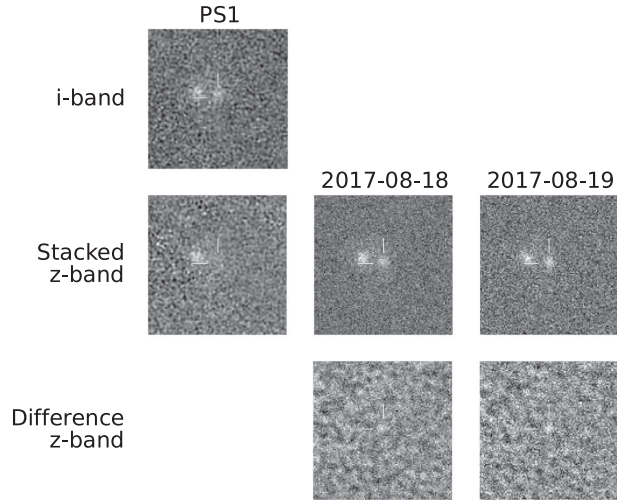


Fig. 8. Stacked and difference z-band images of an off-center candidate J-GEM17bog. The archival PS1 i -band image is also shown. The length of the ticks is $2''$ and the figure size is $20 \times 20 \text{ arcsec}^2$.

et al. 2017). Therefore, we cannot rule out the possibility of any candidates as an EM counterpart of GW170817 from the time variability and the brightness at 1 d after GW170817.

Since the distances to the candidates are unknown except for J-GEM17btc, we evaluate the probability P_{3D} that the associated PS1 object is located within the 3D skymap of GW170817, with a luminosity function of galaxies at a rest wavelength λ , $\phi(\lambda, M)$, derived from rest-frame

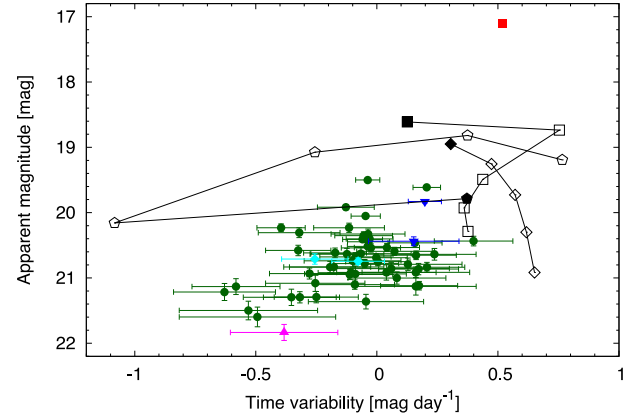


Fig. 9. Magnitude and time variability of the 60 candidates (points with error bars, red square: J-GEM17btc, magenta upward triangle: J-GEM17bog, blue downward triangle: candidates with ROSAT detection, cyan diamond: candidates with NVSS detection, and green circle: the others) and the theoretical kilonova models with an ejecta mass of $0.01 M_{\odot}$ at 40 Mpc (points connected with lines, Tanaka et al. 2014, 2017). The models represent dynamical ejecta (diamond), and wind with $Y_e = 0.25$ (square) and 0.3 (pentagon). Filled marks correspond to 1 d after the merger and open marks correspond to 2, 3, 4, and 5 d after the merger. (Color online)

UBVRI luminosity functions (Ilbert et al. 2005), and the Planck cosmology (Planck Collaboration 2014) as follows:

$$P_{3D}(\lambda_j, m_j) = \frac{\int_{D_{\text{mean}} - 3\sigma_D}^{D_{\text{mean}} + 3\sigma_D} \phi(\lambda[\lambda_j, D], M[m_j, D]) A(D) dD}{\int_0^{\infty} \phi(\lambda[\lambda_j, D], M[m_j, D]) A(D) dD}, \quad (1)$$

where D_{mean} and σ_D are the mean and standard deviation of the distance to GW170817 at the position, respectively, $M(m_j, D)$ is the absolute magnitude of a galaxy with observer-frame j -band apparent magnitude m_j at a distance of D , $\lambda(\lambda_j, D)$ is the rest wavelength redshifted from the observed wavelength λ_j with a distance of D , and $A(D)$ is the surface area of observed region at a distance of D .

We evaluated P_{3D} for the PS1 objects associated with the 59 candidates using the r - and/or i -band Kron magnitude in the PS1 catalog. We also estimate the probability of NGC 4993 ($R = 12.09$ mag, Lauberts & Valentijn 1989) associated with J-GEM17btc, which is $P_{3D} = 64\%$. On the other hand, the probability of J-GEM17bog is $9.3 \times 10^{-3} \%$ and the probabilities of the other 58 candidates range from $1.2 \times 10^{-2} \%$ to $2.1 \times 10^{-1} \%$. Furthermore, the possibility that at least one of the 59 candidates including J-GEM17bog is located in the 3D skymap of GW170817 is only 3.2%. Therefore, we conclude that J-GEM17btc is more likely, by more than an order of magnitude, to be the optical counterpart of GW170817 than the other candidates. The large difference between J-GEM17btc and the other 59 candidates stems from the faintness of the associated objects of the other 59 candidates, which prevent them from being registered in the GLADE catalog or NED. Given the luminosity function of galaxies and the comoving volume, the faint objects are likely to be distant objects and thus P_{3D} of them are small. We note that the integrand of the denominator in equation (1) is nearly zero at redshift $z \geq 0.7$ for all 60 candidates and that these results are almost independent of the filters adopted.

4 Conclusions

We have performed a survey for the optical counterpart of GW170817 with Subaru/HSC. Our untargeted transient search covers 23.6 deg^2 corresponding to the 56.6% credible region of GW170817 and reaches the 50% completeness magnitude of 20.6 mag. We find 1551 sources with two-epoch detection, and screen them with catalog matching and visual inspection. The number of final candidates is 60.

We find only one candidate, J-GEM17btc with an associated object firmly located within the 3D skymap of GW170817. In contrast, the other 59 candidates do not have distance information for associated objects. The candidates include one off-center candidate other than J-GEM17btc, but it is associated with the marginally-detected persistent object in the archival PS1 i -band image. The other 58 candidates are located at the center of extended PS1 objects and could be AGN. Four of them are actually associated with ROSAT X-ray sources or NVSS radio sources. However, we cannot rule out the

other 59 candidates from our observations because the kilonova model can have a time variability of -1.0 to $+1.0 \text{ mag day}^{-1}$ at early epochs.

Hence, we evaluate the probability that the PS1 object associated with the candidate is located within the 3D skymap of GW170817. The probability of NGC 4993 associated with J-GEM17btc is 64%, while the possibility, that at least one of the other 59 candidates is located in the 3D skymap, is only 3.2%. Therefore, we conclude that J-GEM17btc (a.k.a. SSS17a/DLT17ck) is the most likely and distinguished candidate to be an optical counterpart of GW170817. The same conclusion is brought by another untargeted wide-field survey, made with the Dark Energy Camera (DECam: Soares-Santos et al. 2017). We note that J-GEM17btc is intensively observed by many telescopes, satellites, and instruments (e.g., Abbott et al. 2017a; Utsumi et al. 2017).

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