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First gravitational-wave burst GW150914: MASTER optical follow-up observations

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ABSTRACT

The Advanced LIGO observatory recently reported the first direct detection of the gravitational waves (GWs) predicted by Einstein & Sitzungsber. We report on the first optical observations of the GW source GW150914 error region with the Global MASTER Robotic Net. Between the optical telescopes of electromagnetic support, the covered area is dominated by MASTER with an unfiltered magnitude up to 19.9 mag (5σ). We detected several optical transients, which proved to be unconnected with the GW event. The main input to investigate the final error box of GW150914 was made by the MASTER-SAAO robotic telescope, which covered 70 per cent of the final GW error box and 90 per cent of the common localization area of the LIGO and Fermi events. Our result is consistent with the conclusion (Abbott et al. 2016a) that GWs from GW150914 were produced in a binary black hole merger. At the same time, we cannot exclude that MASTER OT J040938.68−541316.9 exploded on 2015 September 14.

Key words: gravitational waves – stars: black holes.

1 INTRODUCTION

The Advanced LIGO (aLIGO) observatory recently reported the first direct detection of gravitational waves (GWs) (Abbott et al. 2016a,c) as a merger of two black holes with masses of $36^{+5}_{-4}\,M_{\odot}$ and $29^{+4}_{-4}\,M_{\odot}$, which is in good agreement with the population synthesis (Lipunov, Postnov & Prokhorov 1996) prediction for binary stars (Lipunov, Postnov & Prokhorov 1997a,b,c; Lipunov et al. 2017).

There are several arguments that electromagnetic (EM) radiation should appear before, during and after a GW event. Lipunov & Panchenko (1996) showed that if the merging process involves at least one magnetized neutron star, one can expect short radio and optical precursor non-thermal emission, like that produced by pulsars. Hansen et al. (2001) later illustrated the idea by Lipunov & Panchenko (1996) for a detailed electrodynamic model. Blinnikov et al. (1984) were the first to show that a neutron star merger can be accompanied by a powerful EM burst. After the merger (Clark, van den Huevel & Sutantyo 1979), a part of the radioactive matter can be ejected leaving behind a so-called kilonova (Li & Paczynski 1998; Metzger et al. 2010; Tanvir et al. 2013; Berger, Fong & Chornock 2013) or a rapidly rotating self-gravitating object and a

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Figure 1. Global MASTER Robotic Net sites and LIGO interferometers (both in the USA), which were involved in the LIGO GW150914 event investigations. Information about each MASTER-Net observatory is available in Table 1.

magneto-rotational spinar may form (Lipunova & Lipunov 1998; Lipunov & Gorbovskoy 2008).

We also do not rule out the possibility of a gamma-ray burst (GRB) whose EM radiation is concentrated in a narrow jet (Eichler et al. 1989; Narayan, Paczynski & Piran 1992), which is very unlikely to be detected during the GW event due to the low probability that it is beamed towards the Earth. In the classic scenario, we do not expect any EM emission from binary black holes merging. Nevertheless, this does not mean that all merging black holes are not followed by EM emission. For example, supermassive black holes merging in the centres of galaxies was discussed in Lipunov & Sazhin (1982), who calculated dense globular cluster collapses. However, such a scenario with possible optical emission could be revealed by low-frequency GW projects (LISA type).

Here we will focus in detail on the optical follow-up observation of the first GW event, GW150914, found by the MASTER Global Robotic Net.

Starting from 2003, we began to develop a programme of robotized observations of GRBs and other burst-like phenomena (optical transients). See the MASTER project description (Lipunov, Bogomazov & Abubikerov 2005; Lipunov et al. 2010, 2016b), whose primary aim is to perform optical observations of GRBs. We developed the MASTER global network of identical twin-tube wide-field telescopes with real-time reduction deployed both in the Northern and Southern hemispheres (Lipunov et al. 2010; Kornilov et al. 2012; Gorbovskoy et al. 2012).

This led us to join the Ligo Virgo Collaboration (LVC) follow-up programme in 2015 to detect possible optical counterparts of GW events (Abbott et al. 2016b).

On 2015 September 16 at 19:0:47 UT, we obtained a probability map for the error box of the first GW aLIGO trigger, G184098 (Singer 2015) (GW150914 and G184098 – the two names refer to the same event). Starting from the following night (September 17), we began inspecting the probable GW event sky areas with MASTER network telescopes over the next month at the following sites where the weather and night-time conditions permitted observations: MASTER-Amur, MASTER-Tunka, MASTER-Kislovodsk, MASTER-SAAO and MASTER-IAC. We monitored about 5000 deg^2 of the sky with the depths, down to limiting magnitudes as faint as 20 mag. These results are partially reviewed in a paper by the LIGO/VIRGO EM collaboration (Abbott et al. 2016b).

2 MASTER GLOBAL ROBOTIC NET: THE MAIN PRINCIPES

The MASTER Global Robotic Net[1] includes several observatories: MASTER-Amur, MASTER-Tunka, MASTER-Ural, MASTER-Kislovodsk (Russian Federation), MASTER-SAAO (South Africa), MASTER-IAC (Spain, Canarias) and MASTER-OAFA (Argentina) (Lipunov et al. 2004, 2010; Kornilov et al. 2012; Gorbovskoy et al. 2013). Each has identical wide-field and very wide-field optical channels; see Fig. 1 and Table 1. Each MASTER observatory provides a survey speed of 128 deg^2 h^{-1} with a 19–20 unfiltered magnitude limit per 180 s exposure (wide-field systems depend on Moon phase). Each observatory is equipped with

(i) Twin wide-field optical channel: 40-cm optical telescopes, MASTER-II: 8 deg^2 full field of view (twin 4 deg^2 able to observe in non-parallel mode), *BVRI* and polarizing filters and able to observe without a filter in integral light [unfiltered, calibrated to USNO B1 stars (Monet et al. 2003) as $W = 0.2B + 0.8R$], 4098 × 4098 pixel CCD camera with a scale of 1.85 arcsec pixel^{-1}

[1] http://observ.pereplet.ru/

Table 1. Coordinates of the observatories comprising MASTER-Net.

Site	Longitude λ	Latitude ϕ	Height above sea level h	Country	Note
MASTER-Amur	$+08^{h}29^{m}56^{s}.0$	$+50°19'07''$	215	Russia	Blagoveshchensk, Far East
MASTER-Tunka	$+06^{h}52^{m}16^{s}.1$	$+51°48'34''$	700	Russia	Tunka Valley
MASTER-Ural	$+03^{h}58^{m}11^{s}.2$	$+57°02'13''$	290	Russia	Ural, Kourovka
MASTER-Kislovodsk	$+02^{h}50^{m}04^{s}.0$	$+43°45'00''$	2067	Russia	Caucasus Mountains
MASTER-SAAO	$+01^{h}23^{m}14^{s}.7$	$-32°22'49''$	1760	South Africa	South African Astronomical Observatory
MASTER-IAC	$-01^{h}06^{m}02^{s}.5$	$+28°17'55''$	2422	Spain	Canary Islands, Teide Observatory
MASTER-OAFA	$-04^{h}37^{m}18^{s}.3$	$-31°48'08''$	2430	Argentina	OAFA, San Juan University

(ii) Twin very wide-field optical channel: MASTER-VWF (Kornilov et al. 2012; Gorbovskoy et al. 2013)

The observations with MASTER-Net can be performed in alert, survey or inspection mode. Alert mode is initiated if a target position has good accuracy, that is, when the error box is less than 4°, which is the field of view of each of the MASTER twin telescopes. It is usually used to observe GRBs upon receiving notices from the Gamma-ray Coordinates Network[2] (GCN), neutrino alerts or GW alerts.

When the error boxes of alerts (gamma-rays, neutrinos, etc.) are less than 2 deg^2, MASTER telescopes observe them in alert mode, with co-aligned tubes and different polarizers (total of 4 deg^2) (Pruzhinskaya et al. 2014). For alerts with larger error boxes (e.g. Fermi gamma-ray alerts; GW alerts, etc.), MASTER observations are performed with the twin telescopes offset to cover $2° \times 4°$, i.e. 8 deg^2, imaging three exposures per field (Lipunov et al. 2016b; Gorbovskoy et al. 2016), i.e. inspection mode. MASTER survey mode is used for the regular survey and search for optical transients (OTs), when there are no alerts, and is the usual mode of operation. The MASTER control and planning software has been developed to select preferred locations for the survey. The planner takes into account the previous coverage rate of the area; the angular distances from the Galactic plane, the Moon, the Sun and the ecliptic; and the current field of view. It takes into account the number of supernovae (SNe) Ia in the field and GRBs discovered within the previous 24 h. During the survey, each area is observed several times with automatically chosen exposure times ranging from 60 to 180 s, depending on the presence of the Moon. The observation time varies from 10 min to 1 h, depending on the Moon phase, weather conditions and the remaining observing time.

For large coordinate error boxes, such as a GW alert or GRB alert more than 1 h after the trigger, we use inspection mode, which combines the alert and survey modes. First, the centre of the error box is observed in alert mode during the time $t - T_0 < 5$ min (T_0 is the trigger time and t is when the alert comes to the MASTER server). Then the telescope switches to survey mode inside the error box area. The 1σ error box is covered first, then larger 2σ and 3σ regions. The error boxes are covered using the same algorithm as for survey mode. Each area is observed three times in 5-min intervals with exposure times of 60 s. Inspection mode allows us to cover big areas quickly and search for all types of OTs. If the same error box can be observed by two or more MASTER-Net telescopes, then they are commanded to cover different fields. Thus, the rate of coverage grows in proportion to the number of telescopes.

The main unique feature of the MASTER system is our dedicated software, which allows new OTs to be discovered on the MASTER images within 1–2 min after each CCD readout. This software gives us the following information: full classification of all sources found in the image, the data from previous MASTER-Net archive images for each source, full information from the VIZIER data base[3] and all public sources (e.g. Minor Planet checker), derivation of orbital elements for moving objects, etc. For transient detections, real astrophysical sources are unlikely to be represented by just 1–2 pixels in the image. Such sources are very likely to be artificial and are screened out by the transient search task. The MASTER software discovers OTs not by the difference between the previous and current frames, but by fully identifying each new source in every frame, with respect to a reference image. If there is a galaxy in the neighbourhood of a transient, the software automatically checks for this and classifies the OT as a possible SN (PSN), after manually checking its position to find any faint Galactic source that is below the optical frame limit along the line of sight in MASTER or POSS archive images.

If there are no VIZIER sources within 5 arcsec and the brightness is constant over one or two nights, it may be a cataclysmic variable (mostly of the dwarf nova type). If the brightness increases and fades away again over the course of several tens of minutes and there is a red or infrared detection in VIZIER, it is likely to be a dMe flare star (UV Cet) object.

The discovery strategy for OTs consists of the following. The objects detected in a MASTER image can be classified into three categories:

(i) Known objects: These objects are identified by matching their coordinates and magnitude with catalogues.
(ii) Flare or eclipse: The object is found at the location as a catalogued object, but has a significant negative or positive magnitude difference.
(iii) Unknown object: The object is absent in the catalogues.

We then compare the object lists to filter out uncatalogued moving objects and to start analysing the transients found. Each candidate is carefully analysed by a human to investigate its nature further. If we have several images of the OT in the current outburst or previous outbursts from 2008 by one of the MASTER observatories, we analyse its light curve and the MASTER archive images to clarify its most probable classification.

We have discovered over several years with this MASTER software about 1200 OTs of 10 different types:

(i) GRB optical counterparts
(ii) SNe (including superluminous ones)
(iii) novae
(iv) quasi-stellar objects and blazar flares
(v) short transients (possible orphan GRBs)

[2] http://gcn.gsfc.nasa.gov/

[3] http://vizier.u-strasbg.fr/viz-bin/VizieR-4 (Ochsenbein, Bauer & Marcout 2000)

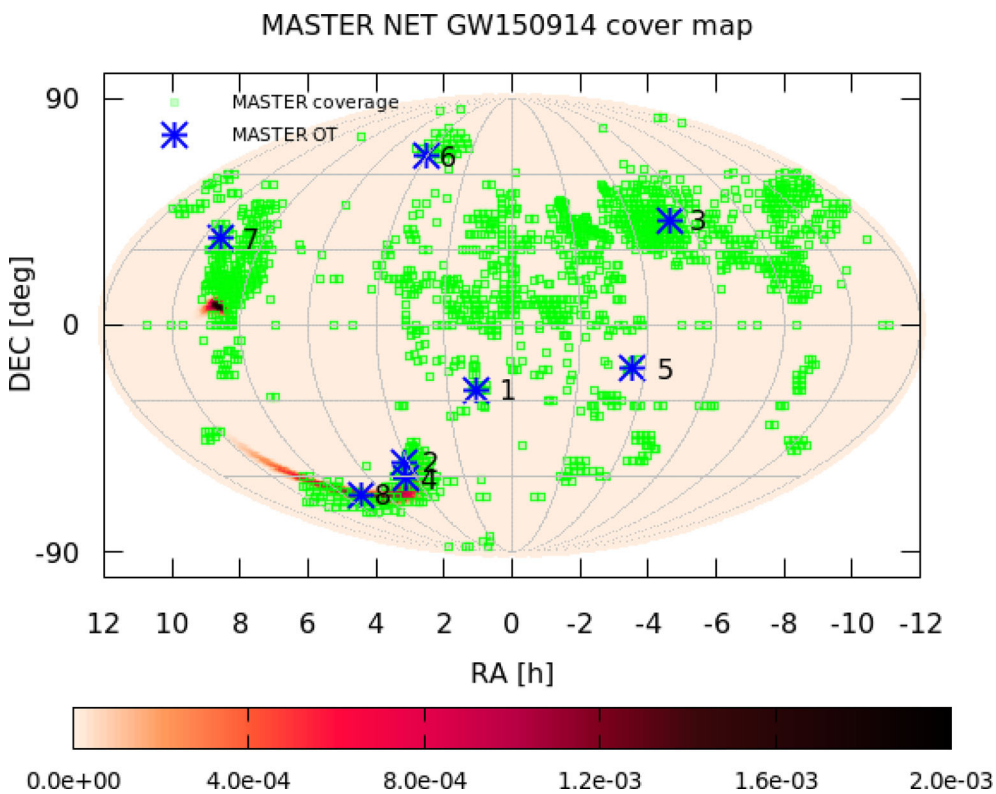

Figure 2. Complete map of the sky survey carried out by the MASTER robotic telescope net at the time of the GW150914 observation, from 2015 September 14 to 22. Each field (marked with a green square) was observed at least three times and covers 4 deg^2 of the sky down to a limiting magnitude of 19–20 mag. The colour palette indicates the LIGO GW150914 probability distribution over the sky. The probability is nowhere zero, and, therefore, any field can be considered. The blue asterisks show the OTs discovered by MASTER during the inspections of the LIGO error box and are described in the paper. Details are presented in Table 3.

(vi) dwarf novae
(vii) antinovae (ε Aur-type) (Lipunov et al. 2016c)
(viii) R CrB and other cataclysmic variables (VY Scl type)
(ix) UV Cet type flare stars
(x) potentially hazardous asteroids and comets[4]

This fully automatic detection MASTER system is very useful for investigating error boxes of GWs with an area of initially dozens of hundreds of square degrees.

3 GW150914 OBSERVATIONS

The GW150914 alert message with the error region was received just over a day after the GW event, on 2015 September 16. All telescopes in the MASTER network began observing different parts of the GW150914 error region when the corresponding areas became visible. The first images in response to the GW150914 alert were taken at the MASTER-SAAO observatory at 2015 September 16 20:18:11 UT. The initial LIGO error region consisted of two elongated areas. The first area was in the Southern hemisphere and the second one was near the celestial equator. Both areas were somewhat difficult to observe. It was possible to observe the two areas only several hours before sunrise. In addition, most regions of the error box were less than 40° from the Sun, where no regular survey-mode observations were performed with MASTER telescopes.

The southern GW150914 localization area was observed with the MASTER-SAAO telescope in the Southern hemisphere (South African Astronomical Observatory). The area near the equator was observed by the MASTER-IAC, MASTER-Kislovodsk, MASTER-Tunka and MASTER-Amur telescopes in the Northern hemisphere.

The MASTER-SAAO twin robotic telescope of the Global MASTER Robotic Net (Lipunov et al. 2010) started inspecting the aLIGO trigger G184098 error box 61.25 h after the GW detection, at 2015 September 16 20:18:s11 UT, after receiving the alert at 05:39:58 on 2015 September 16, later published in GCN18330. We later checked the MASTER data base for earlier images taken on 2015 September 14, 15 and 16. We have 30 images starting from 2015 September 15 03:24:22 UT during the usual MASTER-SAAO survey. These images cover 16 deg^2 (the stacked limit is 19.0 mag). So the first optical images were obtained by MASTER 1.094 d before the notice letter and 17.6 h after the G184098 trigger. During the inspection of GW150914 (so-called aLIGO trigger G184098), the 5σ upper limit on our sets was about 18.4–19.9 mag (Lipunov et al. 2015a, Lipunov, Gorbovskoy & Buckley 2015b). On this first night, we observed 212 deg^2, imaged three times for each field during ∼2 h. The Large Magellanic Cloud and Milky Way are near the centre and east edge of the error region, respectively. The coverage map is presented in Fig. 2 and will be discussed later.

MASTER-SAAO and other telescopes of MASTER-Net continued to survey the error-box region over the coming days. Up to 2015 September 22, we took about 9500 images. which covered more than 5200 deg^2 of sky. More than 920 images were inside the eventual error box of GW150914 and cover 590 deg^2. Each area was covered several times. The full coverage map is shown in Fig. 2. The total probability of the source location in the covered fields depends on the specific error box and reaches 56 per cent. The

[4] http://observ.pereplet.ru/MASTER_OT.html

Table 2. MASTER-Net survey parameters during the GW150914 inspection. The parameters listed include the covered sky area, the covered sky area inside the GW150914 error box and the total contained probability for all four possible GW150914 localizations. cWB, LIB, BSTR and LALInf are abbreviations for different variants of LIGO data processing for event localization. They are described in detail in Abbott et al. (2016b, paragraph 2, page 14) and references therein.

Site	Area full (deg^2)	Area in final error box (deg^2)	Contained probability (per cent) cWB	LIB	BSTR	LALInf
MASTER-Net	5246	590	56	35	55	49
MASTER-SAAO	1072	496	55	33	55	49
MASTER-Kislovodsk	1504	84	1.1	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$
MASTER-Tunka	990	28	0.9	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$
MASTER-IAC	1587	24	1.0	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$
MASTER-Amur	438	0	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$
MASTER-Ural	261	0	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$

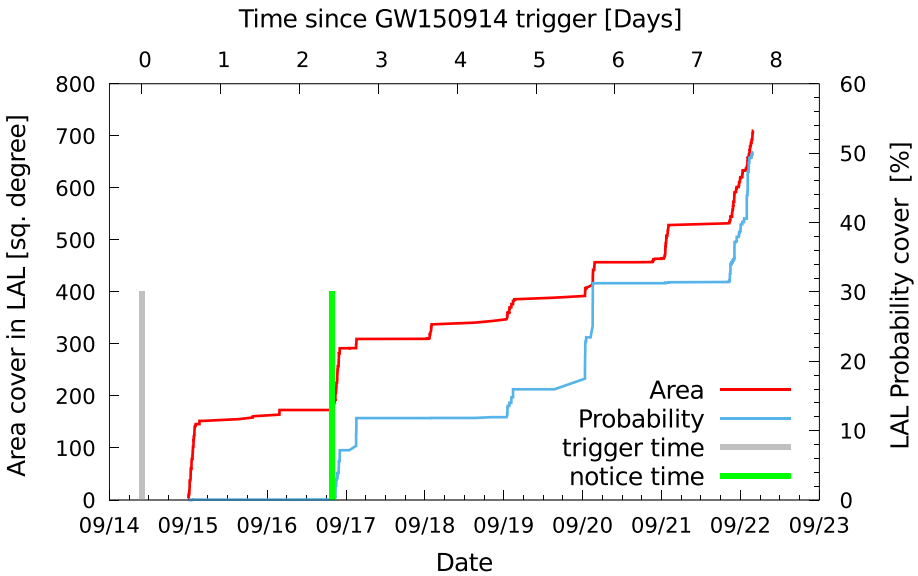

Figure 3. Time history of coverage of GW150914 error box (cumulative curve).

values for all error boxes and for all observatories of MASTER-Net are listed in Table 2.

As follows from Table 2, the most coverage of any GW150914 error box was by MASTER-SAAO. We observed locations of GW150914 (G184098) from 2015 September 15 03:24:22 UT (in a regular sky survey, before the GW trigger) until 2015 September 22 03:25:02 on every night for ∼2 h before sunrise, when the field reached 15° altitude at this site (Lipunov et al. 2016a). We missed the full night of 2015 September 18 due to bad weather. Our observations covered about half of the full probability area of the final error region, down to a limiting magnitude of 19.0. The time history of coverage of the GW150914 error box (cumulative curve) is presented in Fig. 3.

4 OPTICAL TRANSIENTS

Our survey revealed eight OTs observed at different observatories of the MASTER network during the 8 d period for which MASTER searched for an EM counterpart following the GW150914 alert. We mark all the newly discovered OTs with blue asterisks in Fig. 2 and list them in Table 3 with brief comments. Five of these eight OTs are in areas with very low probability (which, however, is greater than zero in all cases). The probability of their association with the GW source is extremely low.

The remaining three OTs are inside the error region. These OTs are marked by a bold font and asterisks in Table 3 and Fig. 2, respectively. We discuss these in more detail below.

4.1 MASTER OT J040938.68−541316.9: a possible SN discovery

The MASTER-SAAO auto-detection system discovered an OT source at (RA, Dec) = $4^h9^m38^s.68$, $-54°13'16.9''$ on 2015 September 16.87912 UT (Gress et al. 2015a). The OT unfiltered magnitude was 17.3 mag (the limit is 17.8 mag). The OT was seen in five images. There are no minor planets at this location. We have a reference image without the OT taken on 2015 February 14.89772 UT with an unfiltered limiting magnitude of 20 mag.

This OT was classified as a PSN, being 0.9″W and 3.6″N of the centre of the galaxy PGC421615 (B_{tot} = 18.4 mag). The discovery and reference (with the best limit) images are shown in Fig. 4.

Later (after it was discovered on 2015 September 16), this SN was observed several times in white (unfiltered) light during the regular survey performed by the MASTER-SAAO telescope: 2015 September 24; 2015 October 17, 18 and 19; 2015 November 25; 2016 January 26 and 2016 February 18. Several (three or more) frames with this sky area were available for each night; however, we analysed only the combined images to increase the

Table 3. OTs discovered by the MASTER-Net auto-detection system during GW150914 observations. The discovery date (Date column) is expressed as the day number in 2015 September. For example, 16.017 means that the transient was discovered at 2015 September 16.017 UT. Type is the transient type: SN, supernova; PSN, probable supernova; DN, dwarf nova outburst. Mag is the unfiltered magnitude of the transient defined as $0.8 \times R_2 + 0.2 \times B_2$, where R and B are the corresponding USNO B1.0 catalogue magnitudes. Site indicates the particular observatory of MASTER-Net that discovered the transient. Ligo Prob is the LIGO probability at the OT location in the sky.

N	OT name	Date (UT)	Type	Mag	ATel/CBET	MASTER Site	LIGO Prob	Comment
1	MASTER OT J010654.20−254135.1	16.017	DN	18.3	8087	SAAO	$\leq 10^{-42}$	Ampl > 2 mag
2	**MASTER OT J040938.68−541316.9**	16.879	SN	17.3	8065	SAAO	1.9×10^{-6}	PSN in PGC421615
3	MASTER OT J183934.91+414404.2	16.890	SN	17.2	8064	IAC	1.3×10^{-37}	Ultraluminous PSN
4	**MASTER OT J042822.91−604158.3**	16.909	DN	18.2	–	SAAO	3.6×10^{-6}	Ampl > 3.8 mag
5	MASTER OT J202411.65−172512.5	17.862	DN	17.9	8065	IAC	8.2×10^{-42}	Ampl > 2.7 mag
6	MASTER OT J040140.85+670613.9	19.848	SN	17.7	8075	Tunka	$\leq 10^{-42}$	PSN in PGC2695052[a]
7	MASTER OT J092544.53+341636.1	21.072	SN	15.6	8077/4192	Kislovodsk	9.3×10^{-41}	SN2015aq(II,UGC05015)
8	**MASTER OT J070747.72−672205.6**	21.995	DN	16.9	8087	SAAO	8.4×10^{-6}	Ampl > 3.4 mag

[a]The PSN in PGC2695052 was discovered by the MASTER auto-detection system during the Fermi trigger 464366002 inspection.

Figure 4. Discovery (left and middle) and reference (right) images for the PSN, MASTER OT J040938.68−541316.9. It is associated with the $z = 0.054$ galaxy PGC421615 and was discovered by MASTER-SAAO inside the LIGO GW150914 error box during the first night of the GW150914 inspection. North and east are to the top and left, respectively, and each chart is 5 × 5 arcmin in size.

signal-to-noise ratio. We list the results of the photometry in Table 4. Formally, the SN reached maximum light on 2015 September 24; however, the measured magnitude differed only slightly from the magnitude at the time of its discovery, and the error bars overlap. The SN appears to have reached its maximum light between the observations of 2015 September 16 and 2015 October 24; see Fig. 6 (Cappellaro et al. 1997; Hamuy et al. 2002; Di Carlo et al. 2002; Stern et al. 2004).

To study this SN and its host galaxy in more detail, we took deep photometric images in B, g', r', i' and z' of the area on 2016 March 3 with the SALTICAM CCD camera of the 10.4-m Southern African Large Telescope (SALT) at the SAAO (Buckley, Swart & Meiring 2006; O'Donoghue et al. 2006), as part of a spectroscopic follow-up programme of MASTER OTs. In some of these images, the SN can be seen clearly in different filters 170 d after its discovery. We present the results of our photometric measurements in Table 4.

The scarcity of available photometric data prevents a determination of the SN type. Photometric data listed in Table 4 are consistent with the assumption that we are dealing with a Type Ib/c or IIp SN discovered near maximum light. The 2015 September 16 and 24 observations were evidently made near the maximum when the flux does not vary appreciably. Thus, analysing the SN light curves[5] (Cappellaro et al. 1997; Hamuy et al. 2002; Di Carlo et al. 2002; Stern et al. 2004), we can say that the SN explosion considered could have been on 2015 September 14.

[5] https://c3.lbl.gov/nugent/nugent_templates.html

Table 4. Brightness measurements for the SN MASTER OT J040938.68−541316.9.

Observatory, instrument	Band	Julian date	Exposure time	Magnitude	Magnitude error
MASTER-SAAO	C	245 7282.384	480	17.2	0.1
MASTER-SAAO	C	245 7289.597	180	17.1	0.1
MASTER-SAAO	C	245 7312.469	1620	18.0	0.2
MASTER-SAAO	C	245 7313.470	2160	18.0	0.2
MASTER-SAAO	C	245 7314.503	720	18.1	0.2
MASTER-SAAO	C	245 7352.453	180	≤19.2	–
MASTER-SAAO	C	245 7414.438	180	≤20.2	–
MASTER-SAAO	C	245 7437.308	13 500	≤20.6	–
SALTICAM	r′	245 7452.309	100	21.7	0.1
SALTICAM	g′	245 7452.312	100	21.1	0.1
SALTICAM	B	245 7452.313	100	21.5	0.1

On 2016 March 10, we obtained a low-resolution (∼300) spectrum, covering 3400–10 000 Å, of the host galaxy PGC421615 in a 1800 s exposure. The spectrum, shown in Fig. 5, has identified emission lines of [O II 3727], Hα and [S II], resulting in a red-shift determination of $z = 0.054$, implying a relatively close galaxy. The red

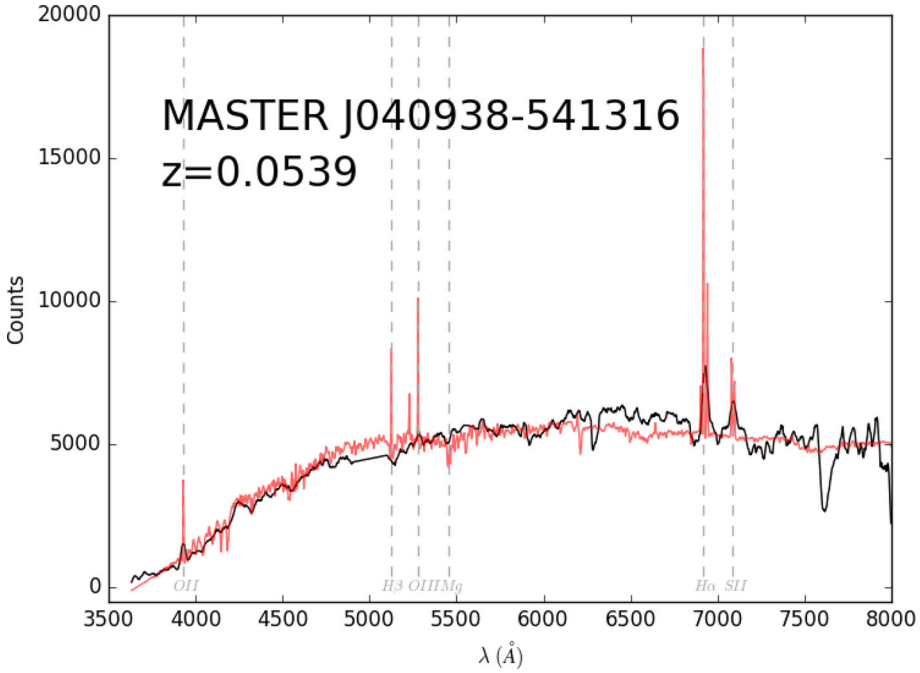

Figure 5. SALT spectrum of the MASTER OT J040938.68−541316.9 host galaxy. Black is the spectrum of the galaxy (with emission lines of [O II], Hα and [S II] present, indicative of star formation) and red is the template spectrum.

shift was determined through cross-correlation of the observed spectra with the template spectra. It was cross-correlated with template 27 from the SDSS spectra templates[6] (Crawford et al. 2010). Note, that the GW150914 red shift is $z = 0.09^{+0.03}_{-0.04}$ (Abbott et al. 2016a).

MASTER OT J040938.68−541316.9 was observed with GROND (Greiner et al. 2008) to learn more about the quiescent properties. Simultaneous imaging in $g'r'i'z'JHK_s$ for MASTER OT J040938.68−541316.9 started on 2016 August 13 at 09:02 UT, with exposure times of 2160 s in $g'r'i'z'$ and 1800 s in JHK for each source. Observations were done at an airmass of 1.3 (1.2), a mean seeing of 1.3 arcsec (1.5 arcsec) and a clear sky.

GROND data were reduced in the standard manner (Krühler et al. 2008) using PYRAF/IRAF (Tody 1993; Küpcü et al. 2008). The optical/near-infrared imaging was calibrated against GROND zero points for $g'r'i'z'$ and the 2MASS catalogue for JHK_s imaging. This results in typical absolute accuracies of ±0.05 mag in $g'r'i'z'$ and ±0.07 mag in JHK_s.

In the field of MASTER OT J040938.68−541316.9, we clearly see the galaxy at RA(2000.0) = $4^h9^m38^s.8$, Dec(2000.0) = $-54°13'21''$, but nothing at the position of the OT, which is 4 arcsec to the north. In the $g'r'i'$ bands, we clearly detect galaxy emission at the position of the transient, while in the z' band, no emission above the background is seen. The 2σ upper limit at the OT position is $z'(AB) > 23.7$ mag (host-subtracted).

4.2 MASTER OT J070747.72−672205.6: a possible U Gem type (dwarf nova outburst) detection

The MASTER-SAAO auto-detection system discovered an OT source at (RA, Dec) = $7^h7^m47^s.72$, $-67°22'5.6''$ on 2015 September 21.99535 UT (Gress et al. 2015b). The OT unfiltered magnitude was 16.9 (the limiting magnitude $m_{\rm lim} = 19.2$). The OT was seen in eight images. We have reference images without the OT taken on 2014 December 25.02683 UT and 2015 February 24.863 UT with unfiltered magnitude limits of 20.0 and 20.3 mag, respectively.

There is a USNO B1 star (0226−0200013) 3.8 arcsec from the object with blue and red magnitudes of $B2 = 20.97$ and $R2 = 20.01$, respectively. This is too far away to be associated with our object, because the typical position uncertainty is 0.7 arcsec, but AAVSO identified our OT with this star, namely a cataclysmic variable of the U Gem (dwarf nova) subclass, i.e. an accreting white dwarf in a binary system.[7] The discovery and reference images are available at Fig. 7. We suggest that the most probable classification is a dwarf nova, but in just our position, the only value that will change will be the amplitude of the current outburst (taking into account the 22 mag POSS limit).

4.3 MASTER OT J042822.91−604158.3 discovery: possible dwarf nova outburst

The MASTER-SAAO auto-detection system discovered an OT source at (RA, Dec) = $4^h28^m22^s.91$, $-60°41'58''.3$ on 2015 September 16.90907 UT. The OT unfiltered magnitude is 18.2 mag (the limit is 19.2 mag). This OT was seen in three images on 2015 September 16 21:49:04.329, 21:55:28.386 and 22:01:50.134 UT, and is absent in the images on 2015 September 24 02:33:07 with $m_{\rm lim} = 19.6$. This implies the OT is not a SN, despite being close (18.7 arcsec) to a galaxy (GALEXASC J042825.42−604155.3) with unknown red shift.

We have reference images without the OT also taken on 2015 August 01 01:13:02 UT with an unfiltered magnitude limit of $m_{\rm lim} = 18.4$, on 2015 November 13 21:10:14 UT with unfiltered $m_{\rm lim} = 20.3$ and on 2016 March 01 18:38:04 UT with unfiltered $m_{\rm lim} = 21.3$. There are no known sources in the VIZIER data base

[6] http://classic.sdss.org/dr5/algorithms/spectemplates/

[7] https://www.aavso.org/vsx/index.php?view=detail.top&oid=410052

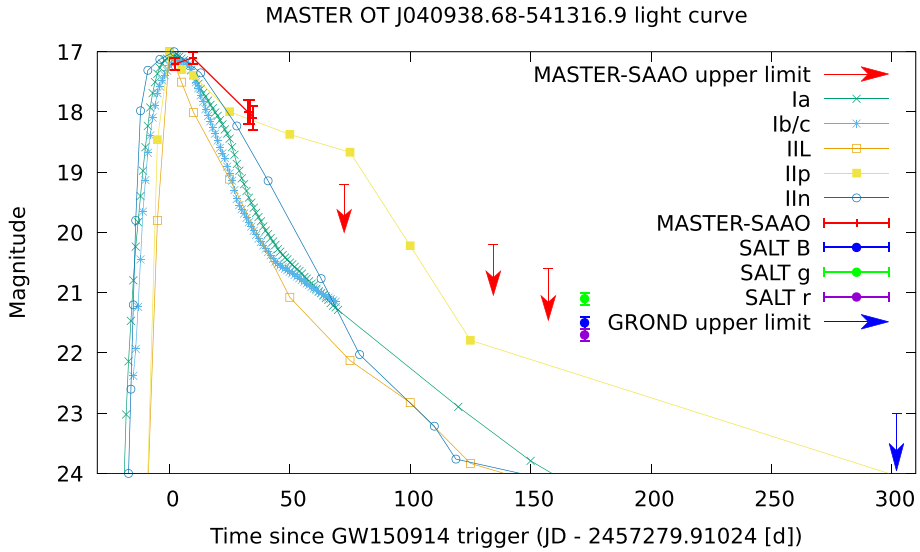

Figure 6. MASTER OT J040938.68−541316.9 light curve taken with MASTER, SALT and GROND, plus examples of different types of SN behaviour (Cappellaro et al. 1997; Hamuy et al. 2002; Di Carlo et al. 2002; Stern et al. 2004).

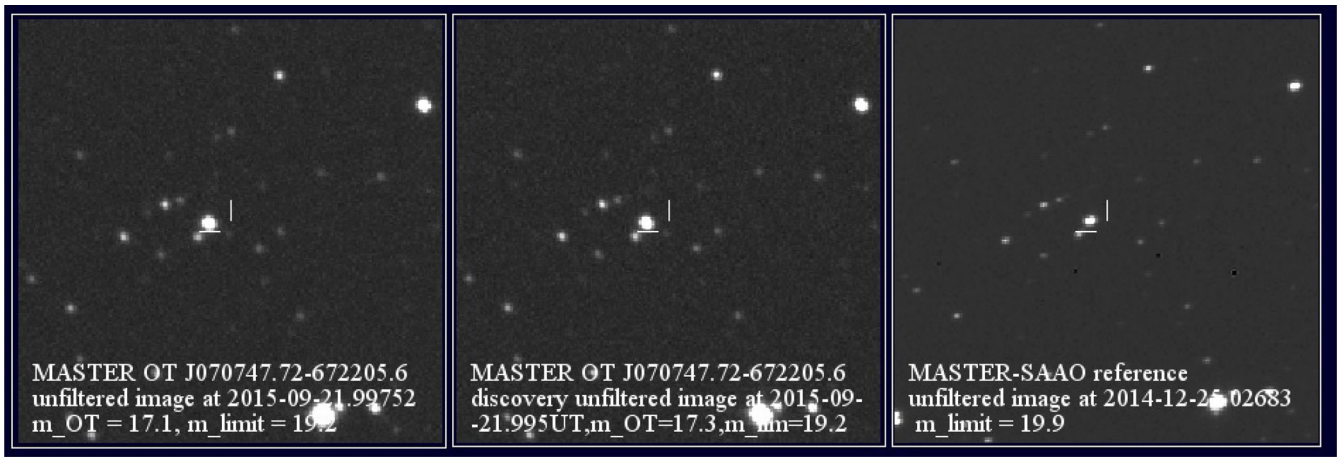

Figure 7. A U Gem type dwarf nova (possible, but most probable classification) discovered by MASTER-SAAO inside the LIGO GW150914 error box. The discovery (left and middle) and reference (right) images of this OT are shown. North and east are to the top and left, respectively, and each chart is 5 × 5 arcmin in size.

(22 mag POSS limit), so we suggest the amplitude of the outburst is more than 3.8 mag. The most likely classification of this OT is a dwarf nova outburst, or possibly a dMe flare star. Catalina Real Time Survey (Drake et al. 2009) and NSVS (Wozniack et al. 2004) also observed this area, but have never discovered a transient at this location. There are also were no minor planets at this location at the time of the MASTER observations. However, if one looks at the GALEX map, there is a marginal detection near our position, which may be evidence for accretion on to the white dwarf, i.e. there is the possibility of it being a dwarf nova outburst at maximum with a hot accretion disk.

The discovery and reference images are shown in Fig. 8.

MASTER OT J042822.91−604158.3 was observed with GROND (Greiner et al. 2008) to learn more about the quiescent properties. Simultaneous imaging in $g'r'i'z'JHK_s$ for MASTER OT J042822.91−604158.3 started on 2016 August 12 at 09:02 UT, with exposure times of 2160 s in $g'r'i'z'$ and 1800 s in JHK for each source. Observations were done at an airmass of 1.3 (1.2), a mean seeing of 1″.3 (1″.5) and a clear sky.

In the field of MASTER OT J042822.91−604158.3, we find a clear optical point source at position RA = 67.09535°, Dec = −60.69953°, corresponding to RA(2000.0) = $4^h28^m22^s.88$, Dec(2000.0) = −60°41′58″.3 (±0″.3), which is fully consistent with the MASTER transient position. We, therefore, identify this object as the optical counterpart of MASTER OT J042822.91−604158.3.

We measure the following magnitudes, all in the AB system (not including the systematic calibration offset error):

(i) $g' = 22.19 \pm 0.04$ mag
(ii) $r' = 22.40 \pm 0.05$ mag
(iii) $i' = 22.63 \pm 0.08$ mag
(iv) $z' = 22.47 \pm 0.09$ mag
(v) $J > 21.2$ mag
(vi) $H > 20.8$ mag
(vii) $K > 19.8$ mag

This spectral energy distribution is rather blue, consistent with a temperature of 9000 K. This is inconsistent with a late-type

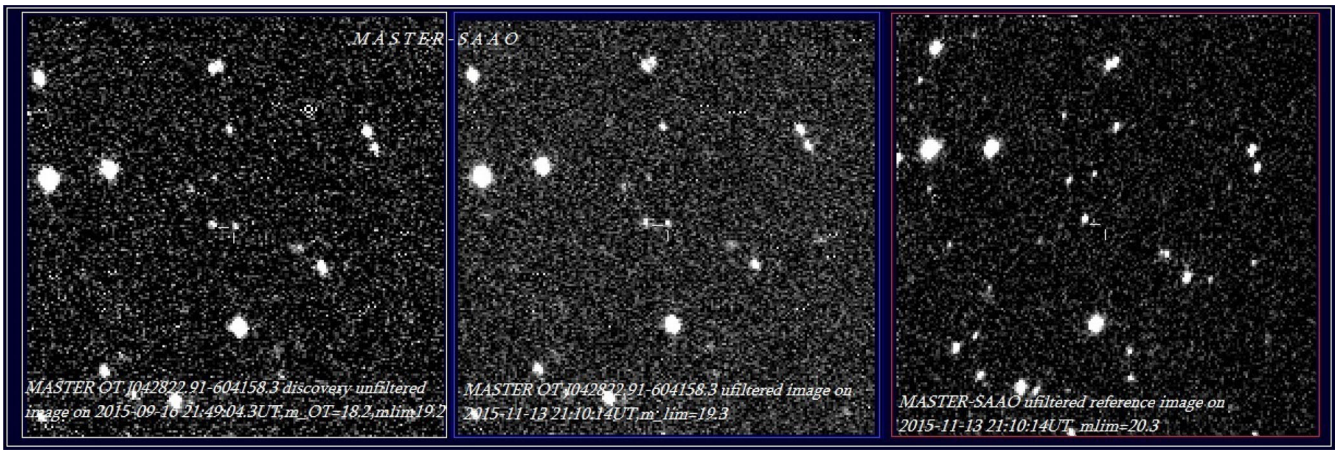

Figure 8. Discovery (left and middle) and reference (right) images for MASTER OT J042822.91−604158.3, a possible dwarf nova, discovered by MASTER-SAAO inside the LIGO GW150914 error box during the first night of GW150914 inspection. North and east are to the top and left, respectively, and each chart is 5 × 5 arcmin in size.

K/M flare star and given the outburst properties of MASTER OT J042822.91−604158.3, this suggests a dwarf nova origin.

If this is a superluminous SN (which may be brighter than the host galaxy at 3.8 mag), it must be present in our images of day 8 on 2015 September 24, but there is no optical source on September 24 with $m_{\rm lim} = 19.6$. A superluminous SN cannot decay to 1.4 mag (18.2–19.6) during 8 d, at the same time this is the usual decay for the dwarf nova scenario. The GROND counterpart cannot be the host galaxy for these reasons.

5 COMPARISONS WITH OTHER TRANSIENT DETECTION OBSERVATIONS

A number of observatories took part in EM support of the LIGO/VIRGO collaboration event GW150914, including optical telescopes (DECam, iPTF, KWFC, MASTER, PanSTARRS1, LSQuest, SkyMapper, SWIFT-UVOT, TAROT, TOROS and VST-ESO), gamma- and X-ray observatories (Fermi LAT, GBM, Swift, IPN, MAXI and INTEGRAL), near-infrared (VISTA) and radio (ASKAP, LOFAR and MWA); see Abbott et al. (2016c).

The contained probability of the initial sky maps is dominated by MASTER (710 deg^2 out of 900 deg^2, see Table 2; Abbott et al. 2016c). While the MASTER Global Robotic Net covered the largest survey area, other large areas were also covered by Pan-STARRS1, intermediate Palomar Transient Factory (iPTF, Kasliwal et al. 2016), Dark Energy Camera (DECam, Soares-Santos et al. 2016), VLT Survey Telescope (Brocato et al. 2015a,b) and La Silla-QUEST (Rabinovitz et al. 2015).

After the completion of the LIGO/VIRGO GW150914 localization reductions and after we received the final error region, we considered only those transient events that appeared within it. In the following, we will discuss La Silla QUEST OTs and a Fermi event that were included in the final error region.

5.1 La Silla QUEST survey

La Silla-QUEST survey (LSQ) operated the 10 deg^2 QUEST camera on the 1.0-m ESO Schmidt at La Silla, Chile, and covered a 40 deg^2 area, finding three OTs (Rabinovitz et al. 2015). Following the LSQ discovery, PESSTO (Smartt et al. 2015, 2016) reported on these transients, including two SN Ia discoveries (Takats et al. 2016). The three LSQ transients were:

(i) LSQ15bbj: $V_{\rm mag} = 19.8$, coordinates: 07:16:14.45, −69:36:00.36; SN Ia

(ii) LSQ15bbc: $V_{\rm mag} = 19.5$, coordinates: 07:06:16.63, −67:12:12.24; a likely variable star, with positions in the USNO, WISE and GALEX catalogues

(iii) LSQ15bbb: $V_{\rm mag} = 17.4$, coordinates: 07:25:16.51, −69:04:01.20; a SN Ia

LSQ15bbb and LSQ15bbj were outside the MASTER survey area in 2015 September. They appeared to be normal-looking Type Ia SNe (see the PESSTO classification; Takats et al. 2016) and were almost certainly unrelated to the GW trigger, because the white dwarfs in SNe Ia do not collapse to black holes, which was the type of event determined for GW150914.

LSQ15bbc was in the MASTER survey with unfiltered $m_{\rm OT} = 18.9$ on 2015 September 21 23:53:18.814 UT, and we saw its previous outbursts on 2015 January 13 00:02:20.937 with unfiltered $m_{\rm OT} = 18.2$ and on 2015 February 24 20:33:22.089, with $m_{\rm OT} = 19.7$. This is a known USNO B1 star, with blue $B2 = 21.00$ and red $R2 = 19.03$, and it is also a GALEX source. This is, therefore, a possible dwarf nova cataclysmic variable with repeated outbursts, or possibly a dMe flare star. All these observations imply there is no connection to the GW150914 black hole merger.

5.2 Fermi gamma-ray event

The participants of the programme to search for EM counterparts of LIGO GW events included many X-ray and gamma-ray observatories, such as the Konus-Wind Russian–American experiment, the INTEGRAL, Swift and Fermi satellites, and the MAXI experiment (Abbott et al. 2016a). However, Fermi was the only team to report the discovery of a very weak short-lived (less than 1 s) GRB by the GBM detector, 0.4 s after the GW trigger (Connaughton et al. 2016). The burst had an energy of $\sim 3 \times 10^{-7}$ erg and was discovered post facto in the archive record of the gamma-ray background after receiving the G184098 alert. The luminosity of the GRB, if we assume that it occurred at the same distance as the GW150914 event (500 Mpc; Abbott et al. 2016d), can be estimated as $E_{\rm Fermi} \sim 2 \times 10^{49}$ erg s^{-1}, which is much lower than the typical isotropic luminosity of GRBs.

Fig. 9 shows the localization domain of the Fermi event. Observations by the MASTER-SAAO telescope cover 90 per cent of the

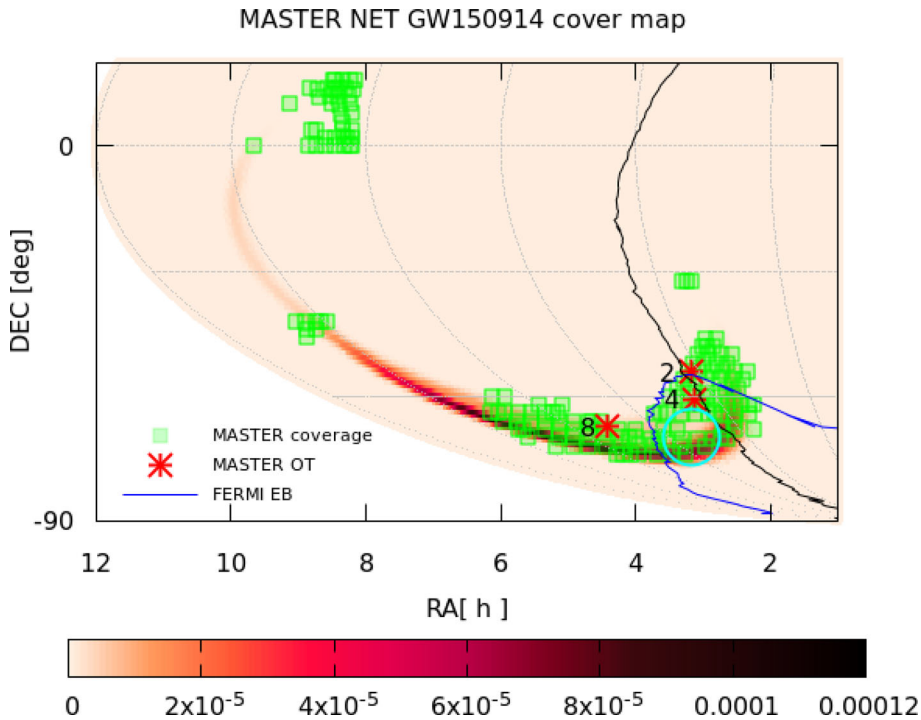

Figure 9. Positions of MASTER OTs compared with the Fermi error box (the blue line), Fermi Earth shadow (the black line) and the LIGO error region (the colour palette). The colour palette represents the probability distribution in the initial LIGO error region. The green boxes show the distribution of the areas covered by MASTER-Net during the inspection of the GW150914 error region. This diagram shows only the fields with probability greater than 1×10^{-8}. The red asterisks indicate the OTs discovered by MASTER during the LIGO error box inspections. These transients are described in detail in the paper and marked with a bold font in Table 3. The light blue (cyan) circle shows the Large Magellanic Cloud region.

total area of the intersection of the LIGO and Fermi error regions. This area was covered only by the MASTER observations and we found no traces of OTs brighter than 19 mag that could be associated with the GW150914/G184098 event (Lipunov et al. 2016a).

Let us now discuss the general possible connection between a GRB and a binary black hole merger. We already pointed out that the emission of standard GRBs is highly anisotropic and the probability of simultaneously recording GWs and GRBs is much less than 1/100 (for example, see Troja et al. 2016). Furthermore, the luminosity of the GRB, if we assume that it occurred at the same distance as the GW150914 event, can be estimated as $E_{\rm Fermi} \sim 2 \times 10^{49}\,{\rm erg\,s^{-1}}$, which is much lower than the typical isotropic luminosity of GRBs. This hypothesis, which was actively discussed by Loeb (2016), has to be rejected due to the following arguments.

Within the framework of standard general relativity, EM emission from the merger of two uncharged black holes can arise only because of the presence of extra matter in the binary black hole, or in its immediate vicinity. For example, Lipunov & Sazhin (1982) noticed as far back as 1982 that a powerful EM burst could arise in the merger of two supermassive black holes surrounded by a dense star cluster, which occurs in almost all active galactic nuclei. This is evidently not the case for GW150914/G184098, due to the low gamma-ray luminosity realized.

However, a certain amount of mass could have accumulated around the black holes via accretion of interstellar gas during the pre-merger stage. This mass should be about $\Delta M \sim 10^{-3}\,{\rm M_\odot}$ if we adopt the typical energy release factor of 10 per cent near accreting black holes. This is the typical mass of a Jupiter-like planet (Cherepashchuk 2016). Although this may seem to be very small, given the $\Delta t \sim 0.4$ s time lag corresponding to a distance of $c\Delta t \sim 10^{10}$ cm, the plasma density near the black holes implied by this mass should be of the order of $\rho \sim \Delta M/(c\Delta t)^3 \sim 1\,{\rm g\,cm^{-3}}$, which is the density of Jupiter. However, such a ring of material or a planet is very hard to explain in a system originally consisting of two blue supergiants (the progenitors of the black holes). A certain amount of matter could have been captured at the stage when the typical distance between the black holes was much smaller than $c\Delta t \sim 10^{10}$ cm. Because of the continuous emission of GWs, the duration of this stage cannot exceed

$$t \sim \left(\frac{I\Omega^2}{2L}\right) \sim 1\,{\rm yr}\left(\frac{A}{10^{10}\,{\rm cm}}\right)^4 \Bigg/ \left(\frac{M}{60\,{\rm M_\odot}}\right)^3 .$$

Thus, t is about 1 yr. The maximum mass that could have accumulated over this year is $\Delta M \sim \dot{M} \times 1$ yr, where the accretion rate can be estimated by the Bondi–Hoyle formula (Lipunov 1992):

$$\dot{M} \approx \pi \frac{(2GM)^2}{v^3}\rho$$
$$\sim 10^{-12}\,\frac{{\rm M_\odot}}{\rm yr}\left(\frac{M}{60\,{\rm M_\odot}}\right)^2\left(\frac{\rho}{10^{-24}\,{\rm g\,cm^{-3}}}\right)\left(\frac{V}{10\,{\rm km\,s^{-1}}}\right)^{-3},$$

where M is the total mass of the black holes, V is the velocity of the motion of the black holes relative to the interstellar medium in the host galaxy and ρ is the density of the interstellar medium.

Obviously, the mass of $10^{-3}\,{\rm M_\odot}$ cannot be accreted in 1 yr, so we conclude that the Fermi GRB event is unrelated to the LIGO GW150914 event.

6 LESSONS LEARNED

As in every first attempt, this first campaign to locate possible EM counterparts of the first confirmed GW detection (GW150914) did

not proceed absolutely smoothly or without problems. First of all, we note that all the automatic alert observations were usually carried out using simple forms of error boxes, for example, a circle (Swift, Fermi GBM and Fermi LAT; see Lipunov et al. 2016b, where we discovered the optical counterpart of the GRB with a 150 deg^2 initial error box in real time) or rectangular (IPN telegrams).

For LVC alerts, we worked with some distribution of probabilities on the sky, with very poorly determined boundaries. The results from the first attempts of the MASTER-robotic system were not only within the error boxes, but also on other areas with small but non-zero probabilities (but these probabilities were not equal to 0 and we had to observe as much of these areas as possible).

Another lesson was learning that there can be multiple LIGO/VIRGO error regions, i.e. several error regions with the same level of probability (see Abbott et al. 2016c). As a result, we spent several nights adapting our observing strategy and preparing an algorithm to account for this.

We recommend that defining the boundaries of an error region (which is not a simple box) is done by the creators of the GW events, rather than by the EM counterpart follow-up teams, as was decided by Fermi, ANTARES and IceCube.

The experience for another LVC alert demonstrated that for a weak signal and more indistinct error boxes, then the current observing algorithm is not really adequate, because small increases in total probability thresholds result in a catastrophic growth of the number of error regions needing to be inspected, with a consequent large increase in the time to conduct a full survey of the total error region. For events with a small (weak) amplitude, the total probability of the observed error region is not really well defined, with the resulting survey limited by the available time.

Nevertheless, the rate of detection of OTs (i.e. the rate of discoveries) during this follow-up inspection appeared higher for the entire MASTER-Net. The overwhelming contribution to the GW150914 EM follow-up survey was made by MASTER-SAAO, located at the South African Astronomical Observatory (SAAO), which is one of the best MASTER nodes in terms of the number and quality of clear nights. For this facility, the average transient survey detection rates (per night) are:

(i) $R = 1.7$ per 1000 deg^2 (averaged Moon week)
(ii) $R = 2.2$ per 1000 deg^2 (averaged Moonless week)
(iii) $R = 2.8$ per 1000 deg^2 (averaged on LIGO/VIRGO inspection week)

We note that the inspection of the GW event GW150914 error box was conducted in practically Moonless conditions (at the end of the night).

There were also some issues concerning the release of information and publications. Some MASTER transient discoveries were announced in the usual manner of published ATel alerts, which are typically every few days, before they were recognized as potential EM counterparts following further error region determinations. An example was the discovery of, perhaps, the most interesting OT reported here, namely the probable SN MASTER OT J040938.68−541316.9, in the area intersected by the LIGO and Fermi error boxes. This information was published as a regularly detected MASTER OT in ATel 8065. Unfortunately, the significance of this discovery was not obvious at the time and no follow-up spectroscopic observations could be performed before it faded, although we have reported here (Section 4.1) on the SALT spectrum taken of the host galaxy much later, establishing its low red shift ($z = 0.054$). However, now (beginning from 2016 September), it looks likely that more immediate information from LVC alerts will be published by LIGO and problems relating to alert delays will not arise.

One other question concerns MASTER resources. We provide each MASTER telescope with sufficient memory and processing power to reduce the MASTER wide-field camera images in real time. That is, the time for image reduction and the addition of new targets into the observing queue does not exceed the time for exposure and CCD readout. Some problems do arise at the inspection phase of images, particularly in areas of high star density in the Milky Way, although such regions are typically low priority and less observed due to the high Galactic extinction of any OTs.

In the specific case of the GW150914 event, MASTER was faced with the problems of the absence of reference sky frames, because MASTER-SAAO had been operational for only ∼10 months at the time of the GW event. Therefore, all inspections for OTs were re-reduced later, once suitable reference frames were determined.

MASTER OT J042822.91−604158.3 (see Table 3) was discovered during this re-reduction phase and it is published here for the first time. This is a probable dwarf nova, although we have information only for its outburst amplitude and no spectrum. We hope that after this publication, some other large telescopes will take some deep images of this area to ascertain if it is a star of our Galaxy, consistent with a dwarf nova.

Many transient alerts are not necessarily followed up with spectroscopic observations immediately for classification, including for MASTER OTs. Such programmes typically require an active high priority target of opportunity status to be able to obtain a spectrum close to maximum brightness, which was lacking at SALT during the time of the GW150914 EM follow-up campaign (now addressed with the instigation of such a target of opportunity observations transient follow-up programme on SALT as of 2016 May). Of course, other telescopes could also have attempted such follow-up observations based on the rapidly published MASTER ATel alerts, though the delays in the release of the GW error regions meant that these observations would typically have had to be undertaken some time after the initial alert, which is one reason why many potential EM transient counterparts to GW150914 were not observed spectroscopically.

7 CONCLUSION

The MASTER Global Robotic Net has carried out an extensive survey of potential OTs as part of a large effort supporting the detection of EM counterparts of the first GW event from aLIGO, namely the GW150914 event (see table 2 in Abbott et al. 2016b,c). The MASTER observations covered the largest area of the defined error regions of all of the optical survey telescopes employed in this endeavour. Despite the difficulty in making observations (the error region was available for observation only a few hours before sunrise), MASTER covered 710 deg^2 inside the initial error region defined by the LIB algorithm (Abbott et al. 2016c) and 590 deg^2 inside the final error region determination, as derived with the revised LALINF algorithm (Abbott et al. 2016c). It should be noted that since the probability is nowhere equal to zero, formally the area outside the 3σ error region can also be taken into account. Observations were, therefore, carried out for these lower significance regions when the 3σ error region was unavailable for observation. In total, during the week after the initial GW150914 event alert, we covered more than 5000 deg^2 with MASTER.

During the inspection of the LIGO GW150914 event, MASTER-Net found eight OTs (see Table 3), three of which are inside the 3σ of the initial and final square error. Of particular note is SN MASTER

OT J070747.72−541316.9, since it could theoretically give bursts of GWs. The analysis (performed in Section 4.1) indicates that the explosion of this SN could have been on 2015 September 14 (the day of the LIGO GW150914 event) and both can and cannot be associated with GW150914.

The others OTs cannot be called a LIGO GW150914 optical counterpart.

The common part of the LIGO and FERMI error boxes, with deduction of the shadow of the Earth, is only a small area of about 100 deg^2 in the Southern hemisphere (see Fig. 9), which was almost completely covered by the MASTER system (∼90 per cent).

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