A search for an optical counterpart to the gravitational wave event GW151226


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A SEARCH FOR AN OPTICAL COUNTERPART TO THE GRAVITATIONAL WAVE EVENT GW151226


ABSTRACT

We present a search for an electromagnetic counterpart of the gravitational wave source GW151226. Using the Pan-STARRS1 telescope we mapped out 290 square degrees in the optical i$_p$ filter starting 11.5 hr after the LIGO information release and lasting for a further 28 days. The first observations started 49.5 hr after the time of the GW151226 detection. We typically reached sensitivity limits of i$_p$ = 20.3 − 20.8 and covered 26.5% of the LIGO probability sky map. We supplemented this with ATLAS survey data, reaching 31% of the probability region to shallower depths of m$_i$ ∼ 19. We found 49 extragalactic transients (that are not obviously AGN), including a faint transient in a galaxy at 7 Mpc (a luminous blue variable outburst) plus a rapidly decaying M-dwarf flare. Spectral classification of 20 other transient events showed them all to be supernovae. We found an unusual transient, PS15dpn, with an explosion date temporally coincident with GW151226 which evolved into a type Ibn supernova. The redshift of the transient is secure at z = 0.1747 ± 0.0001 and we find it unlikely to be linked, since the luminosity distance has a negligible probability of being consistent with that of GW151226. In the 290 square degrees surveyed we therefore do not find a likely counterpart. However we show that our survey strategy would be sensitive to NS-NS mergers producing kilonovae at D_L ≲ 100 Mpc, which is promising for future LIGO/Virgo searches. 

Subject headings: supernovae: general, supernovae: individual (PS15dpn), gravitational waves, surveys

1 INTRODUCTION

The Advanced LIGO experiment detected the first transient gravitational wave signal (GW150914) from the inspiral and merger of a pair of black holes of masses 36$M_{\odot}$ and 29$M_{\odot}$ (Abbott et al. 2016a). This was remarkable not only for being the first direct detection of gravitational waves but the first evidence that binary black holes (BBH) exist, and the largest mass estimates for black holes in the stellar regime (Abbott et al. 2016a). This has been followed by a second discovery, also of a BBH merger signal, with a pair of BHs with masses 14.2$^{+8.3}_{−3.7}M_{\odot}$ and 7.5$^{+2.3}_{−2.2}M_{\odot}$ (Abbott et al. 2016b) on 2015 December 26 (GW151226). LIGO estimate a luminosity distance of 440$^{+180}_{−190}$ Mpc corresponding to a redshift z = 0.09$^{+0.03}_{−0.04}$ (90% limits).

A broad range of teams have begun efforts to follow-up GW signals to detect the putative electromagnetic (EM) counterparts. The first event resulted in 25 teams of observers covering the LIGO sky localization region with gamma ray to radio facilities (summarised in Abbott et al. 2016c). The general assumption has been that BBH mergers will not produce a detectable EM signature. However Fermi may have detected a weak x-ray transient which was temporally coincident with GW150914 (Connaughton et al. 2016), although the reality of the detection is disputed by Greiner et al. (2016). Loeb (2016) suggested a novel mechanism that may produce both a BBH merger and a relativistic jet from the fragmentation of a rapidly rotating core of a single massive star. However if the Fermi hard x-ray detection was real, it is more like a short gamma-ray burst than a long one. Furthermore Woosley (2016) investigated this scenario quantitatively and finds a single star origin to be unlikely. Perna et al. (2016) proposed a short GRB may be formed if the two black holes are formed within a fos-

15 Throughout, we adopt the same cosmological parameters as Abbott et al. (2016b) of $H_0 = 69$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.31$, $\Omega_L = 0.69$. 

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15}$\Omega_M = 0$ and $\Omega_L = 0$.
sil disk which restarts accretion due to tidal forces and shocks during the BBH merger. Hence the searches continue, particularly as a detection would open up a major new way to probe high energy astrophysics, stellar evolution, compact remnants and test modified theories of gravity (Lombriser & Taylor 2016).

Here we present the results of our wide-field search for an optical counterpart to the transient gravitational wave event GW151226 using the Pan-STARRS1 (PS1) and the ATLAS survey telescopes combined with spectroscopic follow-up from Hawaiian facilities and the Public ESO Spectroscopic Survey of Transient Objects (PESSTO).

2. OBSERVING CAMPAIGN OF SOURCE GW151226

To search for optical counterparts to gravitational wave events our collaboration (Smartt et al. 2016) uses the Pan-STARRS1 system (Kaiser et al. 2010) for imaging and relies on the existence of the Pan-STARRS1 3π Survey (Chambers et. al. 2016 in prep) for template images. The PESSTO Survey (Smartt et al. 2015) together with programs on Gemini North with GMOS, the UH2.2m with SNIFS, provide spectroscopic classification. The data for one object discovered here were supplemented with Hubble Space Telescope observations. GW151226 was detected on 2015 December 26 03:39 UTC (MJD 57382.152) and released to the EM community as a discovery on 2015 December 27 17:40 UTC (Abbott et al. 2016). The initial localization generated by the BAYESTAR pipeline (Singer & Price 2016) contained a 50% credible region of 630 square degrees and a 90% region of about 1400 square degrees (to be compared with 90% credible region of 630 square degrees for GW150914 Abbott et al. 2016). We began taking data with the Pan-STARRS1 telescope during the next available dark hours, on 2015 Dec 28 05:08 UTC (11.47 hr after the LIGO information release and 49.48 hr after the event time) and mapped out a region of 214 square degrees on this first night as shown in Figure 1.

The same region was mapped on the two subsequent nights (extending to 273 square degrees). All observations were done with the Pan-STARRS1 $i_1$ filter with a 4-point dither pattern at each pointing centre. The four individual (back to back) 45 sec exposures were co-added to produce a 180s exposure and the Pan-STARRS1 3π $i_1$ reference image (typically having an effective total exposure time of 270-900 sec) was subtracted from this 180s night stack (see Smartt et al. 2016 and Magnier et al. in prep, for more details). On any one night this 180s exposure sequence was repeated multiple times (2-3) in the central highest probability region, giving us some inarnight sampling. The sequence was repeated a further 5 times between 2016 January 02 and January 25 (extending the full footprint to a total of 290 square degrees). The observing cadence and sensitivity are illustrated in Figure 1 and the full PS1 footprint corresponds to 26.5% of the full LIGO posterior probability. This footprint choice was a combination of telescope accessibility of the LIGO localization map and a choice to go deeper on the higher probability regions (Coughlin & Stubbs 2016).

We selected targets with similar filtering algorithms as described in our first paper (Smartt et al. 2016). A total of $2.3 \times 10^7$ detections were ingested into the database (after basic rejections of known defects). Spatial aggregation of detections within 0/5 of each other resulted in the creation of $1.1 \times 10^7$ objects and basic filtering and insistence of two separate detections resulted in a total of $1.7 \times 10^6$ candidate astrophysical transients. Subsequent filtering (obvious dipoles, stellar objects and objects near bright stars) and a random forest machine learning classifier reduced the numbers to 144,000 for which the pixel recognition machine learning technique was employed (Wright et al. 2015 Smartt et al. 2016). Further removal of 3,903 known minor planets left a total of 24,100 objects for humans to scan and this manual process resulted in 85 objects for further investigation.

The human scanning involved removing artefacts that are obvious to the eye but are not properly recognised by the machine learning. As we wanted to err on the side of completion over purity, we set the machine learning threshold to roughly a 20 per cent false positive rate on the ROC curve (see Fig. 7 of Wright et al. 2015 for an illustration). The human scanning removed subtraction and chip defects that are easily distinguished visually.

We note that in the Milky Way plane there were at least a further 43 faint transients which are very likely variable stars that reach above our detection limit on a few epochs. A few could be background hostless supernovae, but their location in the plane suggests they are faint stellar variables.

In addition, the ATLAS 0.5m telescope (Tonry 2011), covered a significant fraction of the northern sky in the first five days after GW151226 as shown in Figure 1. These data were taken during normal ATLAS operations and can be thought of as ATLAS working in serendipitous mode. In future, ATLAS will be able to work in targeted mode in the same way as Pan-STARRS1. A single ATLAS unit, with its 30 square degree cameras can map out 1000 square degrees within 30 minutes. We highlight that just 3 hrs after the GW151226 event detection, ATLAS serendipitously covered 87 square degrees of the sky localization region (2.2% enclosed probability) during the time window 57382.302±0.014. We processed all ATLAS data taken serendipitously in the first 5 days to locate transients as in Tonry et al. (2016). After processing about 575 sq. degrees, the ATLAS coverage increases the total enclosed probability to 36% over the first 5 days from GW151226, getting to median 5σ limits of $m_r \sim 19.0$ (orange filter). Apart from variable stars and CV candidates, we found no other extragalactic transient candidates in this stream.

2.1. Discovery and spectroscopic classification of transients

During our filtering, we removed obvious Galactic stellar variables and known AGN candidates. After removing these contaminants, we found 49 transients which are either confirmed SNe or likely SNe which are summarised in Table 1. As discussed in Smartt et al. (2016), the detected transients are dominated by mostly old supernovae that exploded over an extended period before the GW trigger. The sky position of transients found in the first three days are plotted in Figure 1. Those with spectroscopic classifications are listed along with their redshifts. We suggest that all these objects are unrelated field supernovae, although one object, PS16dpn deserves closer inspection and is discussed in the next section.

We note two objects that are unrelated to GW151226 but are worth highlighting in the context of searching...
Optical counterpart search for GW151226

**Fig. 1.**—

**A:** LIGO sky localization region showing Pan-STARRS1 and ATLAS sky coverage within 5 days of GW151226. **B and C:** Zoom in of our focused region with Pan-STARRS1 and ATLAS sky coverage with transients detected. **D:** 5σ detection limits for all i_P1 images, with the median nightly value marked as red open circles. The black curves are parameterised lightcurves of three different timescales (4d, 20d, 40d) and the blue line is SN1998bw placed at $D_L = 440$ Mpc. **E:** NS-NS mergers expected to be detected within $D_L = 75$ Mpc, as expected in the upcoming 2016 LIGO-VIRGO run. Our 5σ limits are shown with kilonova models. Blue: the disc wind outflows of compact object mergers of Kasen et al. (2015). Red: r-process powered merger model which includes a $^{56}$Ni-dominated wind (Barnes & Kasen 2013). Cyan: merger model with iron-group opacity with $M_{ej} = 0.01 M_\odot$ by the same authors. Green: merger model for opacity dominated by r-process elements, with $M_{ej} = 0.1 M_\odot$ also by the same authors. All in SDSS-like i−band, AB mags.
PS15dqa is a faint transient in the nearby ($D = 7$ Mpc) galaxy NGC 1156. The transient magnitude $i_p = 20.8$ implies $M_i = -8.9$ (including significant Milky Way foreground extinction of $A_i = 0.36$). A Hubble Space Telescope (HST) archive image with the Advanced Camera for Surveys (ACS, in filter F625W) of NGC 1156 shows an object which is astrometrically coincident with PS15dqa to within 0.3''. This is a stellar point source with $m_{F625W} = 20.1$ and hence $M_i = -9.6$. Assuming a bolometric correction of zero this corresponds to $\log L/L_\odot = 5.7$ dex which implies a $50-60 M_\odot$ star that is undergoing brightness variations by a factor of 2. While this scale of variability is known for massive stars of this luminosity, and is unrelated to GW151226, it illustrates our ability to identify faint transients in nearby galaxies. Secondly, PS16ih is a fast optical transient with a 1.3 magnitude fade in 13min on the night of MJD=57397.51 with a faint, red point source in the PS1 reference stack. This is an M-dwarf flare (e.g., Berger et al. 2013) which highlights our ability to pick up fast decaying transients.

2.2. PS15dpm: a type Ibn supernova temporally coincident with GW151226

This object was reported early in the campaign as being of interest because of its rising light curve and very blue spectrum (Chambers et al. 2016). We gathered a multi-color PS1 lightcurve in grizy$\lambda$ filters only (see Inserra et al. 2016 for details) and a full bolometric lightcurve estimated from a black body extrapolation between 0.2–2.5 $\mu$m. A simple Arnett model, as described in Inserra et al. (2013) is shown for the latter with input parameters: $E_{\exp} = 5 \times 10^{53}$ ergs, $M_{B} = 1.9 M_\odot$, $M_{N} = 1.7 M_\odot$. This simply indicates that a $^{56}$Ni model is a poor fit and that type Ibn are not well explained by radioactive powering.

For unusual transients in LIGO/Virgo sky localization regions. PS15dqa is a faint transient in the nearby ($D = 7$ Mpc) galaxy NGC 1156. The transient magnitude $i_p = 20.8$ implies $M_i = -8.9$ (including significant Milky Way foreground extinction of $A_i = 0.36$). A Hubble Space Telescope (HST) archive image with the Advanced Camera for Surveys (ACS, in filter F625W) of NGC 1156 shows an object which is astrometrically coincident with PS15dqa to within 0.3''. This is a stellar point source with $m_{F625W} = 20.1$ and hence $M_i = -9.6$. Assuming a bolometric correction of zero this corresponds to $\log L/L_\odot = 5.7$ dex which implies a $50-60 M_\odot$ star that is undergoing brightness variations by a factor of 2. While this scale of variability is known for massive stars of this luminosity, and is unrelated to GW151226, it illustrates our ability to identify faint transients in nearby galaxies. Secondly, PS16ih is a fast optical transient with a 1.3 magnitude fade in 13min on the night of MJD=57397.51 with a faint, red point source in the PS1 reference stack. This is an M-dwarf flare (e.g., Berger et al. 2013) which highlights our ability to pick up fast decaying transients.

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Fig. 4.— Spectra of PS15dpn from the combined GMOS, PESSTO and SNIFS campaign. The vertical dashed green lines refer to He I and He II lines, while the blue (only shown on left) refer to Hα and Hβ. Right panel refers to restframe days after peak.

The unusual feature of PS15dpn is the detection in the radio by the VLA by Corsi & Palliyaguru (2016), which is quite a luminous 6GHz detection, similar to the relativistic SN 2009bb (Soderberg et al. 2010). Therefore PS15dpn caught our attention because of its rarity, and also the fact that the remarkable pre-explosion outburst found for the nearest Ibn (SN2006jc Pastorello et al. 2007) is still quantitatively unexplained.

Given the temporal coincidence of PS15dpn with GW151226, we estimate the probability of finding a SN Ibn randomly in our sampled field. While we detected PS15dpn at $z = 0.1747$, we would be sensitive to such an object with $M_r \approx -19.6$ (restframe absolute magnitude) to $z = 0.265$. Following the calculations in our first paper (Section 6.3, Smartt et al. 2016), the cosmic rate of core-collapse SNe within $z = 0.265$ implies that within 100 square degrees, there should be 3.1 CCSN explosions per day. We assume an uncertainty in the explosion epoch estimate of PS15dpn of $\Delta t$ days and a relative rate of Ibn SNe of $R_{Ibn}$ (which is the fraction of core-collapse SNe that are Ibn). Then the number of Ibn SNe within a survey area of $A$ square degrees is expected to be

$$N_{Ibn} = 3.1 \frac{A}{100} R_{Ibn} \Delta t$$

For $A = 290$, $\Delta t = 2$, $R_{Ibn} = 0.01$, this suggests $N_{Ibn} = 0.18$. Hence the probability of a false positive (1 or more events) when the expectation value is 0.18 is simply the Poissonian value $p = 1 - e^{-0.18} = 1 - e^{-0.18} = 0.16$. In other words the probability of finding an unrelated SN Ibn exploding within 2 days of GW151226 which is unrelated and a chance coincidence is $p = 0.16$. This is not convincingly low enough to imply a causal link, but is low enough to highlight that future coincidences should be searched for. One could argue that the appropriate value to use for $R_{Ibn}$ is significantly less than 0.01, since radio detections at this luminosity for any Ibc SN are quite rare (Soderberg et al. 2010). Alternatively, type Ibc SNe are much more common overall, which would increase the value for $R_{Ibn}$ significantly. One could speculate that a SN Ibn could potentially be related to a GW source if it was a compact Wolf-Rayet star + BH binary, such as the WR + BH systems in the nearby galaxies IC10 and NGC300 (Crowther et al. 2010; Prestwich et al. 2007). The WR star would need to undergo core-collapse supernova, followed by gravitational-wave driven merger with the BH companion within ~2 days. However, assuming that the star was not in contact with the black hole prior to the supernova, the merger would typically require thousands of years rather than days. A very favourable supernova kick toward the BH could reduce the merger timescale, but would require an implausibly high kick velocity and/or a very low-probability kick direction. However the strongest argument against a link is that the distance estimate to GW151226 is inconsistent with the redshift of PS15dpn (The LIGO Scientific Collaboration and the Virgo Collaboration et al. 2016a). The final probability density function from LIGO drops to zero at $z = 0.1747$ ($D_L = 854$ Mpc) as shown in the detailed companion analysis paper (The LIGO Scientific Collaboration and the Virgo Collaboration et al. 2016c). While the mechanism of Loeb (2016) might predict a rapidly rotating massive star which could conceivably produce both a SN Ibn and GW emission this now seems unlikely from the calculations of Woosley (2016). Some luminous supernovae have been explained by magnetic neutron stars born with millisecond periods (Inserra et al. 2013, 2016), and such an object would radiate gravitational waves if it were elliptically deformed. However a neutron star origin is excluded as the LIGO...
3. DISCUSSION AND CONCLUSIONS

Assuming that none of the transients we found, including PS15dpn, are associated with GW151226 it is useful to set quantitative and meaningful upper limits on potential optical counterparts for BH-BH mergers. These also serve as a guide to our sensitivity to potential future binary neutron star (NS-NS) and neutron star – black hole (NS-BH) merging systems that are more promising systems for producing electromagnetic counterparts particularly redwards of 7000Å.

In Figure 1 we show the 5σ limits of every PS1 image taken during this campaign. As described in Smartt et al. (2016), the 5σ limits are calculated for each of the 51 skycells per pointing of the GPC1 camera data products and the median per night is also plotted. We also plot parametrised lightcurves of three analytic lightcurves with timescales $t_{\text{FWHM}} = 4, 20, 40$ d (as defined in Smartt et al. 2016). These indicate detection limits of $i_P = 20.3, 20.8$ and 20.8 respectively, or $M_i = −18, −17.5, −17.5$ at the luminosity distance of GW151226.

Looking to the future, we plot model lightcurves of kilonovae from compact binary mergers (NS-NS) of Kasen et al. (2013) and Barnes & Kasen (2013) as illustrative examples of our survey capability (the merger models of Tanaka & Hotokezaka 2013 are also of similar luminosity). At the estimated distance of GW151226 of $D_L \approx 440$ Mpc, the predicted fluxes would be very faint (below $i_P \approx 23$). It is expected that NS-NS mergers will be more common by volume and LIGO’s horizon distance for NS-NS detections is a factor of $\sim 5$–10 smaller than for BH-BH mergers, depending on the BH masses (Abadie et al. 2010). During the next science run beginning in the fall of 2016, LIGO is expected to be sensitive to NS-NS mergers within $D_{\text{min}} \leq 75$ Mpc (The LIGO Scientific Collaboration et al. 2016b) and we show in Figure 1 that our survey strategy would be sensitive to these. Ideally, our goal would be to get 0.5 mag deeper, beginning within 24 hrs of the GW alert.

We further show the $i$-band lightcurve of SN 1998bw (Galama et al. 1998) which is the typical energetic type Ic SN associated with long duration gamma-ray bursts (LGRBs). Figure 1 shows that if an energetic type Ic SN accompanies such a GRB event then it would be an unambiguous, bright transient in our survey. We do not find such an object, but caution that we surveyed a maximum of 26.5% of the total LIGO probability region. Our results are encouraging for future searches for the counterparts of NS-NS mergers within about 100 Mpc where the predicted optical and near-infra-red counterparts are within reach.

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TABLE 1

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<td>57385.56</td>
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<td>57395.51</td>
<td>Ia 0.079</td>
<td>SNIFS, D'Avanzo et al. (2016)</td>
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<td>PS15dpn</td>
<td>02 40 41.35</td>
<td>+16 49 52.0</td>
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<td>17.26</td>
<td>57396.88</td>
<td>Ia 0.0292</td>
<td>ASASSN-15un, D'Avanzo et al. (2016)</td>
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<td>PS15pnt</td>
<td>02 07 34.96</td>
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<td>20.64</td>
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<td>Ia 0.041045</td>
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<td>PS15pxy</td>
<td>02 28 22.75</td>
<td>+13 59 19.3</td>
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<td>05 56 14.60</td>
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<td>Likely hostless SN, 0.6′′ fade in 3 days</td>
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<td>02 22 53.41</td>
<td>+19 15 49.9</td>
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<td>+22 36 39.5</td>
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</tbody>
</table>

† MJD for GW151226 is 57382.152

* “Likely SN” means that the transient is not coincident with an observed point source, nor is a known stellar or AGN variable, and does have a candidate host galaxy nearby and a lightcurve that is consistent with being a normal SN.

‡ PS15dov and PS16bpu exploded in the same galaxy UGC2836. Which also hosted SN2001I and SN2003lh.

1 GMOS denotes classification spectra taken for this project with Gemini-N and the GMOS spectrograph with gratings either R150 or R400.

2 PESSTO denotes classification spectra taken for this project with PESSTO as described in Smartt et al. (2016).

3 SNIFS denotes classification spectra taken for this project with the SNIFS instrument on the UH2.2m telescope as described in Smartt et al. (2016).

4 MJD for GW151226 is 57382.152

5 Stellar variables or AGN variability

6 SDSS J002039.86+281525.4, SNIFS, QSO?

7 Likely SN activity

8 Likely stellar

9 AGN

10 Likely M-dwarf flare

11 stellar, CSS100113-035003+370052