First Search for Optical Counterparts to Gravitational-Wave Candidate Events

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LIGO-G1301175-v2
What’s been done?

Between Dec 17 2009 to Jan 8 2010 (winter run) and Sep 2 to Oct 20 2010 (autumn run) gravitational wave (GW) triggers were sent to astronomer partners for follow up.

Analyze GW data, select candidates
Why electromagnetic (EM) follow-up?

Joint GW + EM signal $\rightarrow$ lots of astrophysics

- Position from EM signal improves GW parameter estimation (source position $\rightarrow$ host galaxy $\rightarrow$ redshift)
- Reveal progenitor of EM phenomena
  - Binary progenitor of short GRBs, NS vs. BH, beaming angle.
  - Insights into central engine of long GRBs.
- Probe cosmology and test general relativity

GW networks are all-sky, but most EM is not

- Use a GW first technique to find rare events

Help confirm a GW detection

No one has ever seen a GW event

- Finding counterparts will be exciting....
  But we don’t know what they will look like!
Source Example: Compact Object Mergers

High Energy Photons (X-ray / Gamma Ray):
- Gamma ray burst (seconds)
- Gamma ray burst afterglow (hours)
- Ejecta from a magnetar (10s of minutes)

UV / Optical / IR
- Gamma ray burst afterglow (hours)
- Kilonova (days)

Radio
- Gamma ray burst afterglow (weeks to months)
- Prompt, coherent emission (seconds)

Lots of models! Lots of uncertainty!
Remember: No one has ever seen a NS/NS merger

Possible GWs also from: Supernovae, Long GRBs, etc...
The first search for EM counterparts to GW events

Abadie et al., 2011, A&A 539:A124
Fast, \(~0.5\text{m}\) robotic optical telescopes: ROTSE, TAROT, Pi of the Sky
Large FOV, \(~1\text{m}\) optical telescopes: PTF, QUEST, Zadko, SkyMapper, Liverpool
Radio: LOFAR
GW triggers

**Table 3**

<table>
<thead>
<tr>
<th>ID</th>
<th>Date</th>
<th>UTC</th>
<th>Pipeline</th>
<th>FAR (day$^{-1}$)</th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3821</td>
<td>Dec 29, 2009</td>
<td>15:16:33</td>
<td>Ω</td>
<td>0.66</td>
<td>QUEST collected 12 images</td>
</tr>
<tr>
<td>CWB1</td>
<td>Jan 03, 2010</td>
<td>20:37:22</td>
<td>cWB</td>
<td>1.3</td>
<td>Alert sent Jan 7; TAROT collected 6 images</td>
</tr>
<tr>
<td>G4202</td>
<td>Jan 06, 2010</td>
<td>06:49:45</td>
<td>Ω</td>
<td>4.5</td>
<td>QUEST collected 9 images</td>
</tr>
<tr>
<td>CWB2</td>
<td>Jan 07, 2010</td>
<td>08:46:37</td>
<td>cWB</td>
<td>1.6</td>
<td>QUEST collected 12 images</td>
</tr>
</tbody>
</table>

**Table 4**

<table>
<thead>
<tr>
<th>ID</th>
<th>Date</th>
<th>UTC</th>
<th>Pipeline</th>
<th>FAR (day$^{-1}$)</th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>G19377</td>
<td>Sep 16, 2010</td>
<td>06:42:23</td>
<td>cWB (unmodeled)</td>
<td>&lt; 0.01</td>
<td>ROTSE collected 117 images, TAROT collected 20, Zadko 129, and SkyMapper 21. Blind injection</td>
</tr>
<tr>
<td>G20190</td>
<td>Sep 19, 2010</td>
<td>12:02:25</td>
<td>MBTA</td>
<td>0.16</td>
<td>ROTSE collected 257 images, QUEST 23, Zadko 159, and TAROT 3</td>
</tr>
<tr>
<td>G21852</td>
<td>Sep 26, 2010</td>
<td>20:24:32</td>
<td>cWB (linear)</td>
<td>0.02</td>
<td>ROTSE collected 130 images, PTF 149, CAT 3 DQ</td>
</tr>
<tr>
<td>G23004</td>
<td>Oct 3, 2010</td>
<td>16:48:23</td>
<td>Ω</td>
<td>0.21</td>
<td>ROTSE collected 153 images, QUEST 40, Liverpool - RATCam 22, Liverpool - SkyCamZ 121, and POTS 444</td>
</tr>
</tbody>
</table>
G19377 – blind injection

GW skymap shows the probability per square degree that each location is the true source direction.

Timeline showing when each telescope observed the requested fields.

Aasi et al., 2013, arXiv:1310.2314
### 8 Projects, 6 Analysis Pipelines

<table>
<thead>
<tr>
<th>Project</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUEST</td>
<td>Catalog based search</td>
</tr>
<tr>
<td>TAROT</td>
<td>Cuts on galaxy coincidence, dimming rate, etc.</td>
</tr>
<tr>
<td>Zadko</td>
<td>SExtractor plus “in-house” scripts</td>
</tr>
<tr>
<td>Pi of the Sky</td>
<td>Adopted Pi of the Sky transient pipeline</td>
</tr>
<tr>
<td></td>
<td>Catalog search with object data-base</td>
</tr>
<tr>
<td>SkyMapper</td>
<td>Adopted SkyMapper image subtraction SN search</td>
</tr>
<tr>
<td>Palomar Transient Factory</td>
<td>Adopted PTF image subtraction transient search</td>
</tr>
<tr>
<td></td>
<td>Used Berkeley “Transient Classification Pipeline”</td>
</tr>
<tr>
<td>Liverpool Telescope</td>
<td>Image subtraction pipeline built used available astronomy packages</td>
</tr>
<tr>
<td>ROTSE</td>
<td>Adopted ROTSE image subtraction pipeline</td>
</tr>
<tr>
<td></td>
<td>Added automation and “rank statistic”</td>
</tr>
</tbody>
</table>

Aasi et al., 2013, arXiv:1310.2314
Example Analysis - ROTSE

- **Enhanced** the existing image processing pipeline for processing GW events
- Performed a background study to assess the statistical significance of any transients found
- Simulated false transients consistent with a target theoretical lightcurve (kilonova (Metzger et al. 2010), short/long gamma-ray burst (Kann et al. 2010, 2011))

Example Analysis – ROTSE G19377
Background Distribution

![Graph showing the distribution of background pointings. The x-axis represents the ranking statistic, and the y-axis represents the fraction of pointings. The line for the foreground is shown in black, and the line for the background is shown in blue.](image-url)
Example analysis – ROTSE G19377
How far could we have detected a source?
Overall - did we find anything?

No convincing optical transient counterpart was found

Remember - the gravitational wave triggers were unlikely to represent true astrophysical events.

Lessons of this work should prove useful in the up-coming ‘advanced’ generation of GW detectors.

The LIGO and Virgo Collaboration have recently made an open call for partners to search for EM counterparts to GW events discovered with the next generation of detectors.

Next generation of GW detectors are due to start taking data again c. 2015, however they won’t reach design sensitivity until c.2020+