Rapid response gravitational wave follow-up with the PIRATE robotic telescope

Conference or Workshop Item

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1. Introduction

The existence of gravitational waves (GW) has been theorised for over 100 years, but they were not detected conclusively until 2015 (Abbott et al., 2016), owing to their incredibly weak signal. These signals were detected by the LIGO-Virgo Collaboration (LVC) using incredibly sensitive interferometers, that are up to 4km in length. And since 2015 they have detected gravitational waves emanating from 6 compact binary mergers, and all but one of these were binary black holes. However last August the LVC detected gravitational waves from a binary neutron star merger for the first time (Abbott et al., 2017).

In addition to the GW signal, an electromagnetic counterpart (EM), known as a kilonova (see Figure 1), was also discovered. After a brief gamma ray flair, the optical signature of this counterpart was dominated by the kilonova process, but this signal rapidly faded by several orders of magnitude in just 10 day (Figure 2). That is why follow-up observations such as these require rapid response times to catch them before they disappear. The observations taken by several observatories of AT 2017gfo showed that, with an initial magnitude of $m_1=17$ (i-band) (Coulter et al., Soares-Santos et al., 2017), it was visible to the northern hemisphere at this time: it would then have also been observable with PIRATE. Nevertheless, PIRATE look back at the EM follow-up campaign for O2 and the results of which are given later.

4. Results

The second LIGO observing run (O2) ran from 30th November 2016 to 25th August 2017, and during this period they released 10+ alerts to the observing community. One of these PIRATE was able to follow up 70% up to some degree. For 4 of these we have 7+ days of observations, which cover around 35 fields of view, in total we obtained 70 nights of observations comprising of over 2,000 images.

During processing of all the data we concluded that no unexpected transients were detected in our data, however all the alerts we followed up originated from binary black hole mergers which aren’t expected to produce an electromagnetic counterpart.

The LVC Figure 7 shows the lightcurve of a previously known W Uma class variable star, that was serendipitously detected while performing our follow-up observations, and there are dozens more similar examples to this in our data set. Lastly the plot in Figure 8, shows the lightcurve of the MASTER 0J0337+7215S, which was a Type Ib supernova discovered pre-discovery by the MASTER group while performing follow-up observations of another LIGO alert.

We were able to observe this target for over 60 days with PIRATE which demonstrates its capability as a transient follow-up telescope.

2. PIRATE Facility

Previously PIRATE was located at the Observatorio Astronómico de Tenerife West (OAT) on the Canary Islands, Spain, and is a part of a research and teaching telescope. Additionally, the poster describes the methods used to perform rapid follow-up to gravitational wave alerts from LIGO/Virgo, and how the images are processed to look for fading transients. Lastly there is a short summary of results from the last observing campaign, corresponding to the second LIGO observing run (O2).

3. Method

One of the key advantages in using a robotic telescope is the rapid response times it can, achieve for any astronomical alerts of interest, such as gamma-ray bursts and gravitational waves. However to utilize this it was necessary to create a bespoke pipeline that would process the incoming alerts quickly, but more importantly, without any human intervention. The result was a Python script built on one written by Leo Singer (Singer, 2015) to receive and process gravitational-wave candidate alerts from Advanced LIGO and Virgo via GCN alerts (Figure 5 & 6).

The alerts contain a sky localization probability map (known as a skymap) and the key step in this process is deciding which areas of the skymap to observe given their relatively large size. Currently this is done using a simple method of highest to lowest probability and with a maximum number of observations cut-off. However an alternative way would be to target individual galaxies within the search area, such as those in the Gravitational Waves Galaxy Catalogue (White, Dass, & Ohlson, 2011). The PIRATE telescope was available for GCN alerts for a 10-day period after the August 2017 alert. Once the image was calibrated we use the source extraction software SKYEXTRACT (Bertin, 2010) to perform photometry, which then gets passed on to a variable star detection software VAST (Soloskiy & Lebedev, 2017). This generates lightcurves for all the stars in a reference image across the dataset; and it then uses multiple variability indices to shows which stars have high variability across the time series. The index we rely on is the ratio of the variance over the main square successive difference, which highlights stars with variability over longer time scales.

References


Figure 5. A flowchart showing the different stages of LIGO GW trigger analysis. The PIRATE telescope by day in the shadow of the Tenerife observatory. Image Credits: Johannes Baader.

Figure 6. A flowchart highlighting the different stages of the PIRATE alert pipeline.