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Unveiling the Unseen: Challenges in Identifying Electromagnetic Counterparts to Gravitational Waves

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Abstract. The detection of gravitational waves (GWs) from advanced LIGO and advanced Virgo interferometers opened a new era for multi-messenger observations, especially with the coincident detection between the GW event and the gamma-ray bursts (GRB) detection. We report the results of optical follow-up observations of GW events detected by LIGO and Virgo and the limitation of optical observation by small telescopes. Binary black hole (BBH) and binary neutron star (BNS) merger events detected in the first, second, and third observing runs (O1, O2, and O3) were analyzed with a developed processing pipeline. No credible optical sources associated with GW events were detected, and limits were set on the conversion efficiency of energy emitted by GWs to optical light. The fraction of energy emitted by GWs converted into optical light is less than 10^{-5} for BBH mergers. The limiting magnitude and timely observations allowed us to reduce the hypothesis of association between GWs and GRBs in the case of BBH mergers. However, we did not have enough cases to definitively exclude the association between GWs and GRBs for black hole mergers. Due to their distance, no optical observations were available for the five BNS mergers detected in O3. This pioneering experience showed the potential of GW observation in optical follow-up campaigns and highlighted the importance of future GW runs for future observations.

1. Introduction and Method

Gravitational Waves (GWs), forecasted by Albert Einstein's theory of General Relativity, are distortions in space-time. Their detection posed a challenge for nearly a century due to their subtle impact on a human scale. Efforts focused on enhancing detector sensitivity and identifying powerful sources, notably binary neutron stars (BNS). BNS, with their massive density and inherent asymmetry, emitted GWs at detectable levels (Abbott et al. 2017). Some BNS systems were known as binary pulsars, further boosting their potential as GW sources. The breakthrough came in September 2015 with LIGO detecting GWs (Abbott et al. 2016). Surprisingly, the involved masses were from BBH rather than BNS, challenging stellar evolution theories. This revealed the merger of two massive black holes forming a single BH and GWs, with potential for electromagnetic (EM) radiation (Zevin et al. 2017). Distortion in space-time near the merger's final stages might enhance EM radiation (Zhang et al. 2016). Surrounding materials or BH charges could also impact such binary merger events. Accurate sky localization of GW sources enables the search for EM counterparts. However, observing an EM spectrum is crucial for deeper understanding. Initial GW detection triggered a hunt for its EM counterpart, involving 25 teams, yet none were found (Abbott et al. 2016). The challenge lay in the vast sky area, much larger than most telescopes' field of view. Strategies ranged from automated image analysis to advanced machine learning (Noysena et al. 2019). None succeeded, raising the question of whether BBH mergers emit only GWs or also EM radiation. Current EM telescopes lack efficient scanning capabilities for the entire localization boxes, necessitating further research into BBH EM radiation potential. The detection of GW170817 from a BNS merger, along with a gamma-ray burst (Abbott et al. 2017), connected BNS and GRB events for the first time. Combining data from EM and GW detectors pinpointed the sky area accurately, leading to the discovery of an optical counterpart, termed a kilonova (KN), twelve hours later (Metzger et al. 2017). This groundbreaking event opens avenues for extensive exploration in astrophysics.

If we consider the energy constraints from optical observation of GW events within the absence of ever-detected optical transients associated with BBHs, one can compute the upper limit of energy converted into visible light associated with the BBH events. The observing run O1 and O2 had provided energy of ΔE, which was released during GW events' coalescence. The GW150914 gives $\Delta E = 3.0^{+0.5}_{-0.4} M_{\odot}$, and according to Noysena et al. (2019), a small fraction of ΔE can be converted into EM radiation by Equation 1 and 2 to luminosity L as:

$$L = \frac{\alpha \Delta E}{\Delta t} \tag{1}$$

where α is the small fraction of the ΔE energy and Δt is the duration of EM emission. In order to determine the spectral energy distribution of an EM emission from a BBH system, we must spread the EM energy over the EM spectrum. Two possible models for this energy distribution are synchrotron and blackbody radiation. Synchrotron radiation is composed of flat segments separated by spectral breaks, which are determined by the electron energy distribution and magnetic fields. However, no good description of a theory for such an emission exists at this time. The solar blackbody approach is simpler, involving only the assumption of the optical transient being an opaque sphere, though this view is not likely realistic. This model allows us to compare the amount of EM energy of different BBHs.

$$m_{candidate} = -16.12 - 2.5 \log \frac{L}{D^2} \tag{2}$$

Where D is the luminosity distance of the GW source. Small aperture telescopes can easily detect optical transients associated with BBH and BNS mergers. This was demonstrated by the observation of the magnitude 18 transient that lasted 10 hours associated with the BBH GW150914 mergered at 430 Mpc and the BNS GW170817 mergered at 40 Mpc.

The calculated values of α for these events were $\approx 2.65 \times 10^{-7}$ and $\approx 1.72 \times 10^{-7}$, respectively, which is well within the detection range of small telescopes. This shows that small aperture telescopes are capable of detecting and following up on potential optical transients. By combining two existing equations (Equations 1 and 2), we can derive a more general formula to calculate the α factor from observed parameters. This α factor can be constrained by optical observations, even when the underlying emission process is unknown. When an optical detection is not possible, an upper limit on the α factor can be determined, providing an estimate of the maximum amount of energy converted into EM emission.

2. Observation and Data Analysis

We utilize TAROT (Télescope à Action Rapide pour les Objets Transitoires – Rapid Action Telescope for Transient Objects), which is an automated robotic telescope network (Klotz et al. 2008; Boer et al. 2017). It was designed to detect the optical counterparts of GRB through triggers from CGRO-BATSE, Hete-II, Swift, INTEGRAL, and Fermi, thanks to its wide field of view (3.5 to 17.6 square degrees) and rapid response time (less than 10s). This versatility makes the TAROT network a powerful tool in the study of transient objects. The TAROT telescope network has been utilized for optical observations of GRB since 1998 (Klotz et al. 2009), with over 200 GRBs analyzed to date. Additionally, the TAROT network has played a key role in the search for optical transients associated with GW events since the dawn of GW detection. Through these contributions, TAROT has proven its worth as a reliable and accurate tool for astronomical research. The TAROT network consists of three telescopes: TAROT Calern (TCA) located at 6.92353 E, 43.75203 N, and 1320m altitude, TAROT La Silla (TCH) at 70.73260 W, -29.25992 S and 2398m altitude, and finally TAROT Reunion (TRE) at 55.41022 E, -21.19882 S and 991m altitude. TCA and TCH both have an aperture of 250mm and a FoV 1.8×1.8 deg^2, equipped with ANDOR Ikon L936 back-illuminated CCD cameras. TRE has a larger FoV with an aperture of 180mm, and its FLI Proline KAF-16803 CCD camera results in an FoV of 4.2×4.2 deg^2, with a limiting R magnitude of 17 at 5σ for 1-minute unfiltered exposure. The limiting R magnitude for TCA and TCH is at 18.2. The TAROT instruments, with their large FoV, can scan through sky areas of 50 deg^2 in only 10 minutes and have the potential to locate possible GW optical transients. However, the large amount of images produced need to be processed immediately and require a reliable algorithm for identification. In addition, due to the large GW error boxes, new strategies must be developed to maximize the counterpart detection rate.

The observational strategies used in optical follow-ups of GW skymaps have varied between runs O1, O2 and O3. In the first two runs, the TAROT telescopes focused on the high probability localization region and attempted to cover skymaps with repeated observations for each tile to produce the light curve of an unknown object. For example, a 100% coverage of GW170814 was done with small skymaps and revisited all tiles. In contrast, the third run employed a more efficient strategy for observing skymaps. The observation strategy was optimized for optical follow-up of GW skymaps based on Gravitational-wave Electromagnetic Optimization (GWEMOPT), which accounts for tilling that telescopes could observe for both locations in skymaps probability and hours available in the sky. The LIGO and Virgo observatories have detected eleven GW events in their first and second observing runs (run O1 and O2, respectively). TAROT promptly followed up on three of these events, GW150914, GW170104, and GW170814, when the sky maps and tiles were available. For GW150914, the observation was done for 14 days due to its unknown astrophysical origin, while GW170104 and GW170814 were followed up for 7 days and 5 days, respectively. The search strategy focused on a 10% credible region, with the coverage being increased up to a 90% credible region. Despite these efforts, TAROT was not successful in detecting any possible electromagnetic counterparts to the GW events, as reported by Noysena et al. (2019). This indicates the importance of developing better strategies to detect potential electromagnetic counterparts from GW events. The experience from the first two observing runs, TAROT had prepared for the run O3 of the Advanced LIGO and Advanced Virgo (aLIGO/Virgo) GW detectors, and it was ready for the potential GW counterpart. To ensure the successful follow-up of each event, TAROT collaborated with the GRANDMA network (Antier et al. 2019). As part of the collaboration, TAROT was provided with a list of tiles selected by the GRANDMA strategy. GRANDMA network aims to locate the optical transients of GW events with a network of 18 observatories (24 telescopes) located in different parts of the world, including three TAROT telescopes that joined the GRANDMA collaboration during the counterpart and follow-up in the run O3. There is a difference between telescopes connected to the GRANDMA network, and these telescopes have different functions: some of them aim to record only images, helping to search and detect possible optical counterpart candidates, while other telescopes collect spectrometric data for the purposes of classification and distinguishing of astronomical objects. Following the detection of a GW by the aLIGO/Virgo detector, the sky localization is estimated and sent to the GRANDMA network for observation strategy planning. The observation strategy depends on the GW classification; GRANDMA activates small FoV telescopes to record images of selected galaxies located in the skymaps for events such as a BNS merger, whilst large FoV telescopes are used for all GW events, with a strategy divided into tiles for different telescopes. This process has been aided by the GLADE catalog (Coughlin et al. 2019), which provides galaxies as targets in order to improve successful GW identification and follow-up.

The credible region to locate the GW sources at a level of 90% covers hundreds of square degrees. The goal is to record images to cover the entire area of the localization. Knowing the distance of the GW sources provided by LIGO/Virgo notices, we can convert the apparent limiting magnitude of the TAROT telescopes to absolute magnitudes. Figure 2 shows the absolute limiting magnitude of the observations versus the coverage relative to the 90% credible region. We can see 11 GW events covered more than 90%. On the plot, we indicated their names and the types.

Figure 2 provided the TAROT limits for a BBH and a KN detection. TAROT, a 0.25 m diameter telescope, is capable of detecting a BBH-optical source at 90% credible region with an apparent magnitude of 17. However, its sensitivity limits the detection of a kilonova. TAROT telescopes have a low probability of detection, estimated to be 30%. To overcome this limitation, two strategies have been proposed. The first consists of increasing the telescope's diameter to 0.8 meters, thereby increasing the probability of detection to 50%, albeit at the expense of a smaller field of view. The second strategy is to employ multiple robotic telescopes to take simultaneous exposures and combine them afterward.

3. Conclusion

The objective was to identify optical sources associated with gravitational wave events detected by LIGO/Virgo interferometers to improve the knowledge of the nature of the

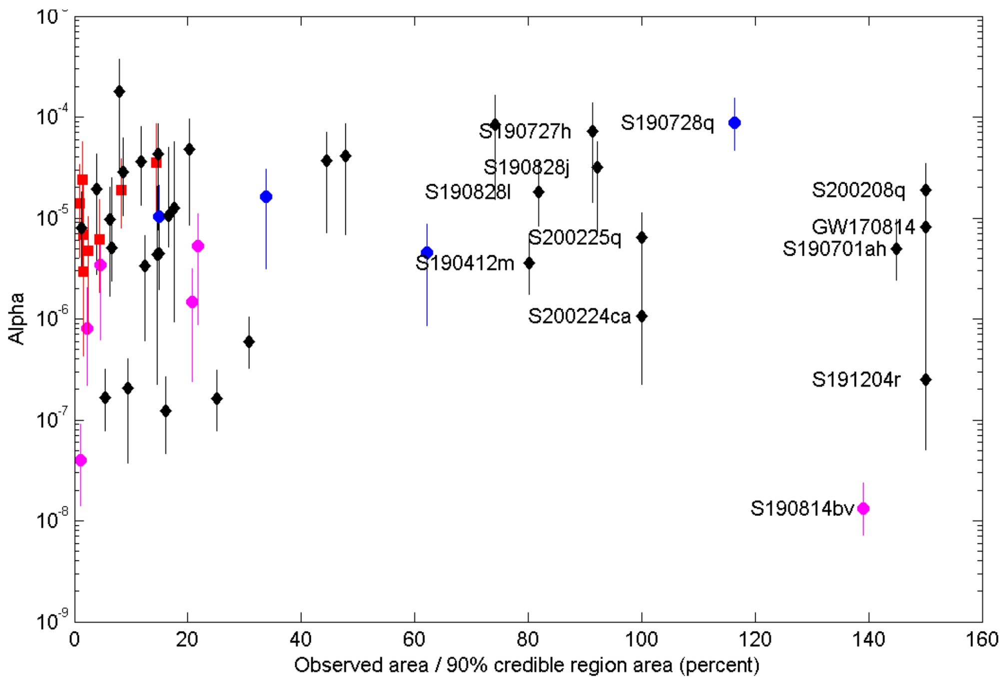

Figure 1. Alpha derived from limits of TAROT observations during the observing run O3 versus the TAROT coverage relative to the percentage of the 90% credible region. Color presents the different merger types: the red square is BNS, the magenta disk is NSBH, the blue disk is MG, and the black diamond is BBH.

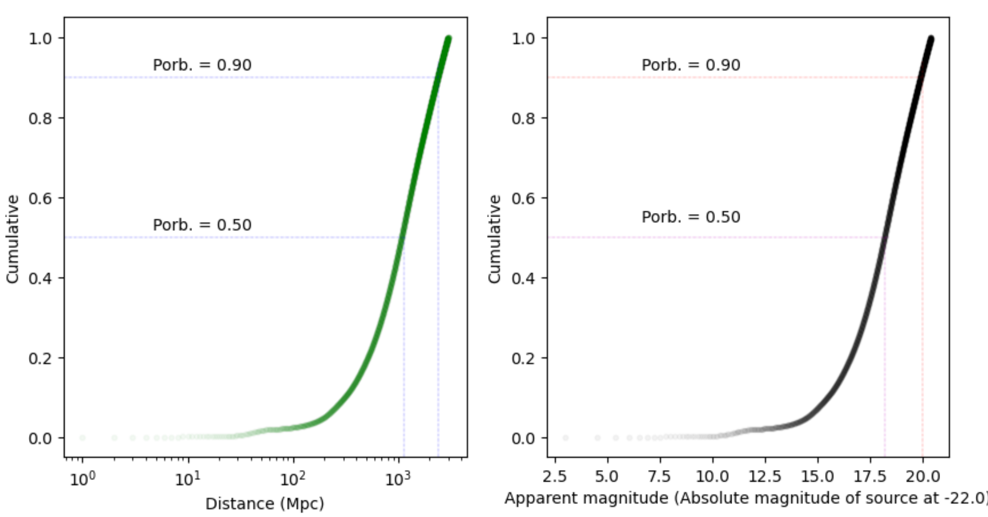

Figure 2. Cumulative probability to find an event according to the distance in the green line (left) and The black line shows the apparent magnitude for SGRB for absolute magnitude at -20.00 (right).

GW sources. The observations were made by the optical TAROT telescopes and cooperated with the targets with GRANDMA collaboration. The image analyzing pipeline based on procedures was tested and applied to the observations performed in response to 50 GW triggers during the runs O1, O2, and O3. A thousand images were analyzed, and hundreds of candidates were checked, but no new credible optical source associated with GW events was found. Results are published in Noysena et al. (2019); Antier et al. (2019, 2020) and in 34 GCN circulars. The limiting magnitude and the short delay in starting optical observations allow us to derive energetic and statistical constraints. If we consider an electromagnetic transient associated with a BBH event emitting isotropic optical light, our observations exclude such a source to be brighter than the absolute magnitude M_R=-25 one hour after the event. The study is also connected to the association of BBH mergers with GRBs as optical transients. GRBs do not emit isotropic light because energy is concentrated in the direction of a jet. TAROT observed three events early enough to be sure that the optical detection should have been positive if the jet was oriented toward the telescope. TAROT observed eight other events with a statistical detection better than 50%. If we make the hypothesis there is always a GRB associated to BBH mergers, we can derive a constraint of $\theta = 35°$ on the opening angle of the ultra relativistic jets of the GRBs. Although our deep and early detection limits reduce the possibility of GRB associations with BBH mergers, we are not able to exclude the association definitively. Concerning BNS, there were no events from LIGO/Virgo closer than 100 Mpc during the run O3. The use of larger aperture telescopes during the next runs is the only way to detect the KN if no new BNS event occurs closer than 100 Mpc.

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