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ELECTROMAGNETIC FOLLOW-UP OF GRAVITATIONAL WAVE SOURCES

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ABSTRACT

Many inspiraling and merging stellar remnants which create gravitational waves also emit radiation as they orbit or collide. These gravitational wave events together with their associated electromagnetic counterparts provide insight about the nature of the merger, allowing us to further constrain parameters about the properties of the binary object. With the start of the third observation run of the Laser Interferometric Gravitational-Wave Observatory (LIGO) and the future launch of the Laser Interferometer Space Antenna (LISA), follow up observations are needed of both transient objects, like the kilonova counterparts to the GW events detected by LIGO, and of ultracompact binary systems, as are predicted to be detected by LISA. Using instruments including Palomar Observatory's Zwicky Transient Facility (ZTF) and Kitt Peak's Electron Multiplying CCD (EMCCD), we will observe these objects and analyze and model their light curves to better understand the astrophysics behind these multi-messenger events.

1. INTRODUCTION

1.1. *Kilonovae*

Massive objects causing a changing quadrupole moment in spacetime, such as the rapid decaying orbit and merger of black holes or neutron stars, produce gravitational waves (GW). From the previous two observing runs with LIGO, there have been 11 GW events detected, most of which were caused by the dramatic collisions of two black holes, one of which was caused two neutron stars.

Although binary black holes are only detected in the GW regime, binary neutron stars (BNS) or neutron star black hole binaries (NSBH) emit in the electromagnetic (EM) spectrum as well. In a neutron star collision, elements heavier than iron are created in a rapid neutron capture process, called r-process nucleosynthesis, in the material ejected violently during the merger. When the r-process elements decay radioactively, this produces a light emission known as a kilonova, which is observable in the optical and infrared region of the EM spectrum. Another EM counterpart to the GW signal is the short gamma-ray burst (sGRB), powered by relativistically outflowing material coming from accretion onto the dense object left behind. The variety of energetic, explosive astrophysical processes triggered by these GW events create EM counterparts ranging from the radio to gamma-ray regime. For example, the binary neutron star (BNS) merger, GW170817, was observed in wavelengths spanning the entire EM spectrum, producing light curves in multiple bands from infrared to optical to ultraviolet, as well as a sGRB detection (Smartt et al. 2017). These observations in tandem with models allows researchers to use multi-messenger Bayesian analysis to calculate properties of the objects and their orbits, as in Coughlin et al. (2018b).

The third observing run of the LIGO-Virgo Collaboration (O3), which began this spring, has already detected a number of GW events, and will continue to detect more in the coming months. With each detection comes the opportunity to follow up the event with multi-messenger astronomy techniques by observing the source in the EM spectrum. Currently, there is both a BNS and a BNS/NSBH candidate that is being followed up on using Palomar Observatory's 48 inch telescope and ZTF wide field camera and the Dark Energy Camera (DECam). ZTF has a 47 square degree field of view, making it ideal for following up sGRB and GW detections, as several potential transient candidates can be localized in one field of view. The Global Relay of Observatories Watching Transients Happen (GROWTH), a global consortium of telescopes and research institutions (including Caltech), are also keeping eyes on the sky. One primary goal of GROWTH is to follow up on transient events, such as kilonovae, AGN, and supernovae, in the hours and days after initial detection.

These photometric observations, if the kilonova candidate is successfully detected, result in light curves that demonstrate dramatic brightening and dimming as the transient evolves (see Figure 1).

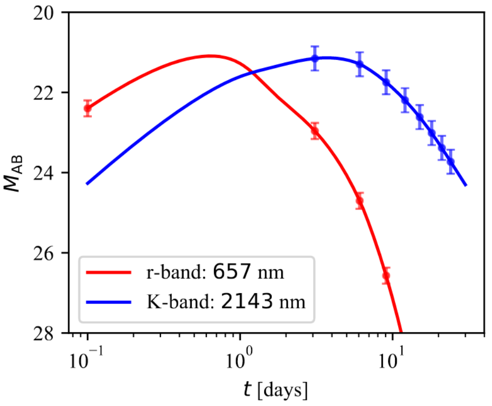

Fig. 1.— Mock light curve of a transient object from Barbieri et al. (2019) showing the characteristic nonperiodic brightening and extreme dimming over time.

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1.2. *LISA Verification Binaries*

In the future, the more sensitive, space based laser interferometer, LISA, will be able to detect slowly inspiraling objects rather than only the compact object merger LIGO has detected thus far. LISA is a similar instrument as LIGO, but operates in a lower frequency range.

One type of object LISA will be able to detect is ultracompact binaries (UCBs). UCBs are degenerate stellar remnants, such as white dwarfs, which orbit each other with subhour periods. According to general relativity, they emit significant gravitational radiation and will dominate GW signals in the mHz regime(Nissanke et al. 2012). Light curves of UCBs are characteristically periodic and often appear sinusoidal, with periods on the order of minutes. When one object eclipses the other, it blocks out some of the light, causing the light from the system to periodically dim and brighten with the orbit.

ZTF recently detected an eclipsing double white dwarf binary system which claims the shortest orbital period discovered so far at 6.91 minutes (Burdge et al. 2019), as shown in Figure 2. The system's ultra-short period and estimated masses predicts it to emit gravitational waves at a frequency detectable by LISA (Prince et al. 2019).

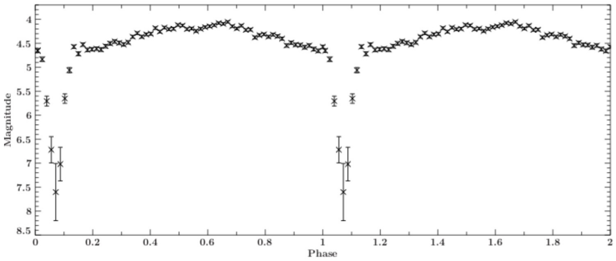

Fig. 2.— Phase folded light curve for the 7 minute period compact white dwarf binary system ZTF J153932.16+502738.8 from Kitt Peak's Electron Multiplying CCD.

To verify and test the future GW detections of UCBs with LISA, we can use optical data. Verification binaries are UCBs detected in the EM regime which will have a signal to noise ratio (SNR) 5 after 4 years integration time with LISA. One survey observed about 50 verification binaries and found about a dozen that meet this requirement (Kupfer et al. 2018). By further characterizing light curves from verification binaries, we can continue to characterize future LISA sources.

2. OBJECTIVES

In my project, I will be using instruments such as ZTF and Kitt Peak's Electron Multiplying CCD (EMCCD) (Coughlin et al. 2019) to observe and analyze EM counterparts of GW events detected by LIGO and to be detected by LISA.

2.1. *Kilonovae*

Kilonovae are useful to study host galaxy properties, r-process production constraints (Rosswog et al. 2018), equations of state of supranuclear density matter (Coughlin et al. 2018a), and to estimate the Hubble constant (Hotokezaka et al. 2018). By constraining a kilonova's parameters with multi-messenger techniques, we can not only paint a fuller picture of the binary system, but can also use the system as an astronomical laboratory.

Tens of thousands of kilonova candidates have been received, and at the moment, are being accepted or rejected as false positives by a human vetting process. First, the GROWTH Target-of-Opportunity Marshal triggers instruments including ZTF and DECam to observe the GW event localized field. Next, these observations are uploaded to the GROWTH Follow-up Marshal database for human vetting. The current pipeline flags candidates by transient properties such as its age, reddening, and how quickly it evolves. Still, the process is mostly manual and often relies on having spectroscopy to rule out false positives, such as asteroids, AGN, and supernovae. Incorporating additional filters as well as machine learning techniques will help automate the vetting process to filter out false positives, and possibly identify kilanovae independently of a GW event.

2.2. *LISA Verification Binaries*

LISA is predicted to detect >27,000 UCBs (Kupfer et al. 2018), as its sensitivity peaks at about 5 mHz which is comparable to the expected frequency of a GW signal from these binary objects (Burdge et al. 2019). However, few of these objects have been identified so far. Recent literature predicts a number of verification binaries that are bright enough to be detectable in the optical, including 143 short period semi detached binary systems with orbital periods less than 25 min (Nelemans et al. 2004), and 200 detached double white dwarfs (Korol et al. 2017), half of which are eclipsing binaries and half of which are non-eclipsing binaries.

Verification binaries are located in our own Milky Way Galaxy, therefore, their surface density in the sky should peak near the Galactic Plane. The current sample as in Kupfer et al. (2018) shows sources mostly in the Northern hemisphere at high Galactic latitudes, suggesting the sample is incomplete. Optical surveys such as those utilizing ZTF should discover more sources to compile a more complete sample of verification binaries.

3. APPROACH

This summer, along with the GROWTH team, I will generally be examining and modeling light curves of various GW sources, either of transients, or of UCBs. In each case, after acquiring the optical EM data, I will process the images by standard photometric data reduction techniques such as bias and dark subtraction and flat fielding. Next, I will use aperture photometry techniques to extract light curves of the transients and analyze their behavior and properties.

3.1. *Kilonovae*

On the kilonova side, I will be working on low latency photometric classification of the objects detected in O3. I will be observing the localization region determined by LIGO and Virgo observations and GRB Fermi satellite detections with the Palomar Observatory ZTF camera, the Kitt Peak EMCCD, and other instruments, in the hours and days following the GW detection. With the overwhelming amount of signals already received and yet to be received in this observing run, we will also need to build a filtering system to determine which signals are actually kilonova detections. Our proposed filter would select criteria based on existing models of kilonova light curves such as Smartt et al. (2017). We would then compare the candidates that passed through the filter to those previously flagged by human vetting during follow up observations. Additionally, as candidates pass through the filter, we will examine them to further refine the filter criteria.

3.2. *LISA Verification Binaries*

On the LISA binary side, I will be searching for periodic light curves from the millions of light curves ZTF has collected. I will be working on efficiently identifying binary objects and analyzing their light curves by phase folding them and using Lomb-Scargle techniques to extract their periods. By modeling their light curves, I will estimate their orbital inclinations and the relative radii of the objects with respect to the semi-major axis of their orbit. With this information, we can also begin to constrain the masses of the binary objects, as well as estimate the gravitational wave strain and frequency detectable by LISA.

4. PROJECT SCHEDULE

I propose the following tentative schedule, which is dependent on new data collected in O3:

- set criteria to filter out false positive transient sources; set criteria to identify periodic UCB light curves (weeks 1-3)

- conduct follow up observations of EM counterparts (weeks 4-6)

- model light curves of transient and Galactic binary (weeks 7-10)

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