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INSPIRALING AND MERGING COMPACT BINARIES IN THE ELECTROMAGNETIC AND GRAVITATIONAL WAVE REGIMES

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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 gravitational wave 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). While these ripples or waves are created by any and every source of gravity, the resulting change in spacetime curvature is negligible except for in extreme cases such as in the early Universe and near dense objects including black holes, neutron stars, and white dwarfs.

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 (BBH) 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. 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).

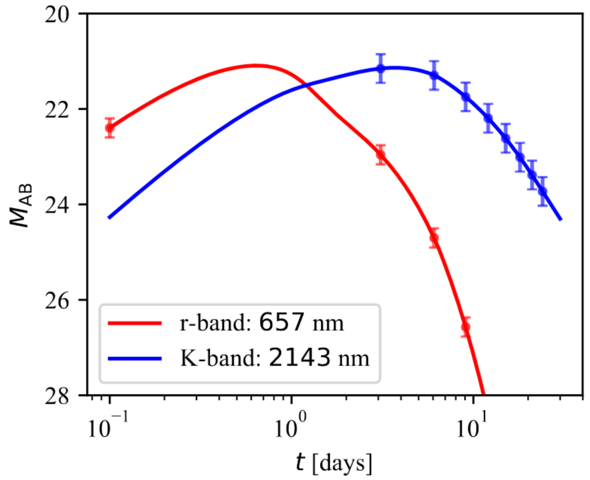

Fig. 1.— Mock light curve of a transient object from Barbieri et al. (2019) showing the characteristic nonperiodic brightening and extreme dimming over time.

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 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). Observational data 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). 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.

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-

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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.

1.2. *Ultracompact Binaries*

Beyond the BNS, BBH, and NSBH detectable by LIGO, our galaxy is rich with a menagerie of binary objects. Many of these objects evolve into dense stellar remnants rapidly orbiting each other in ultracompact binary systems (UCBs). These binaries can be detached or interacting, and are characterized by periods of one hour or shorter (Nelemans and van Haaften 2013). UCBs provide insight into many poorly understood stellar processes including common-envelope evolution, magnetic braking, and massive star evolution (Nelemans and van Haaften 2013). The merger of one type of UCB, double white dwarfs (DWDs) may be progenitors to rare massive white dwarfs, solo neutron stars, subdwarf-O stars, or R Corona Borealis stars (Nissanke et al. 2012a). DWDs in a subhour binary can also help us study tides, white dwarf internal characteristics, and white dwarf viscosity (Korol et al. 2017).

UCBs also emit GW strongly in the low frequency regime which the future space based GW detector, LISA, is highly sensitive to (Nelemans and van Haaften 2013). LISA will detect slowly inspiraling binaries rather than only the compact binary coalescence events LIGO has detected thus far, and is predicted to detect >27,000 UCBs (Kupfer et al. 2018). To verify and test future GW detections of UCBs with LISA, we can use optical data to identify and analyze UCBs in the electromagnetic (EM) regime. LISA sensitivity peaks at about 5 mHz, comparable to the expected frequency of a GW signal from these binary objects (Burdge et al. 2019). Figure 2 compares the LISA sensitivity derived from code[2] from Robson et al. (2019) to the predicted GW signals from a few notable UCBs. According to general relativity, UCBs like these systems emit significant gravitational radiation and will dominate GW signals in the mHz regime (Nissanke et al. 2012b).

Many of the degenerate LISA UCBs are inherently faint (up to 70th mag Korol et al. (2017)) and therefore have not been identified in the EM regime. Only 10s of detached DWDs have been detected thus far. However, recent literature predicts a number of UCBs 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.

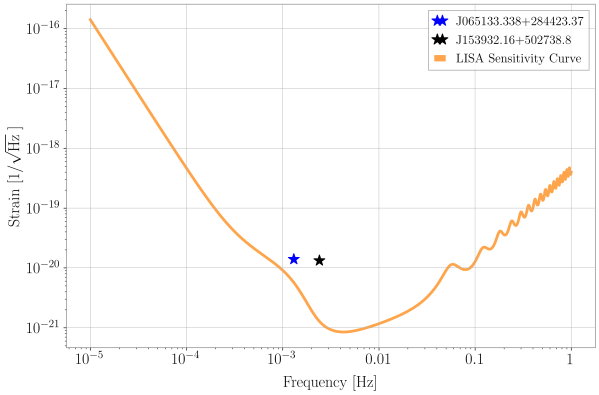

Fig. 2.— Amplitude spectral diagram for LISA showing the expected sensitivity (strain) of the detector at a given frequency. The blue and black points show estimated GW strain of two known UCBs, J065133.338+284423.37, a 12.75 minute period detached white dwarf binary (Hermes et al. 2012), and J153932.16+502738.8, a 6.91 minute binary that is the current shortest period eclipsing binary system (Burdge et al. 2019). Both objects have been studied with time-resolved photometry and spectroscopy and are predicted to be detectable by LISA.

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.

By combining spectroscopy with photometry (and eventually with GW observations), binary parameters can be further constrained than with one observational technique alone. Observing UCBs and measuring binary parameters such as radial velocities, masses, and GW strain, will allow us to test binary evolution models, characterize the astrophysical processes occurring in the systems, and contribute to the sample of verification binaries in preparation for the future launch of LISA.

2. METHODS

2.1. *Photometry*

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.

On the kilonova side, I will be working on low latency photometric classification of the objects detected in O3. To follow-up LIGO detections in the EM regime, 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.

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[2] https://github.com/eXtremeGravityInstitute/LISA$_{sensitivity}$

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. 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. Incorporating additional filters as well as machine learning techniques will help automate the vetting process to filter out false positives, and possibly identify kilonovae independently of a GW event.

On the LISA verification binary side, I will be searching for periodic light curves from the millions of light curves ZTF has collected. As detailed in Burdge et al. (2019), we have period searched light curves taken with ZTF, cross matched candidates to stellar catalogs such as the Roentgen Satellite (ROSAT) X-ray archive, and after visual scans are following-up on interesting targets to confirm real UCBs with the Kitt Peak Electron Multiplying CCD (KPED). Observing UCBs and measuring binary parameters such as radial velocities, masses, and GW strain will allow us to test binary evolution models, characterize the astrophysical processes governing UCBs, and contribute to the sample of LISA verification binaries. I will be working on efficiently identifying binary objects and analyzing their light curves by phase folding them and using Lomb-Scargle and/or Conditional Entropy algorithms 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.

Burdge et al. (2019), using ZTF, recently discovered an eclipsing double white dwarf binary system which claims the shortest orbital period discovered so far at 6.91 minutes, as shown in Figure 3. The system's ultra-short period and estimated masses predicts it to emit gravitational waves at a frequency detectable by LISA, making it well-suited to be a verification binary (Prince et al. 2019).

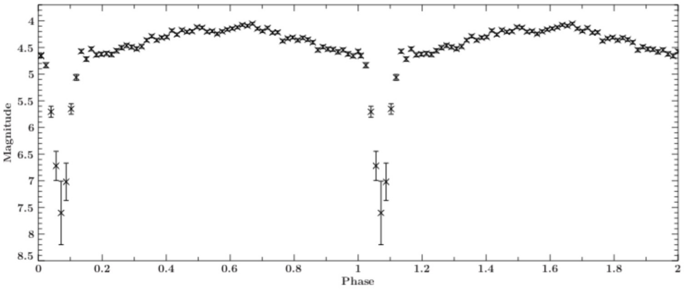

FIG. 3.— Phase folded light curve for the 7 minute period compact white dwarf binary system ZTF J153932.16+502738.8 from Kitt Peak's Electron Multiplying CCD (Coughlin 2019).

Similarly to Burdge et al. (2019), with light curves of UCBs in hand, I will use the `ellc` package (Maxted 2016) to create light curve models to fit to the data. These fits will allow us to measure properties of the binary objects such as the relative radii, inclination, mass ratio. Furthermore, with precise timing and multiple observations over time, we can measure eclipse timing variations to estimate orbital decay, or $\dot{P}$. Figure 4 shows an `ellc` generated light curve for an example UCB.

Not every varying light curve, however, will correspond to an eclipsing binary source. The sample will be contaminated with pulsating white dwarfs and cool spots on the stellar surfaces coming in and out of view as the star rotates. Analysis of the shape of the light curve as well as the object's location on an HR diagram will allow us to identify these non-binary, or non-eclipsing binary sources.

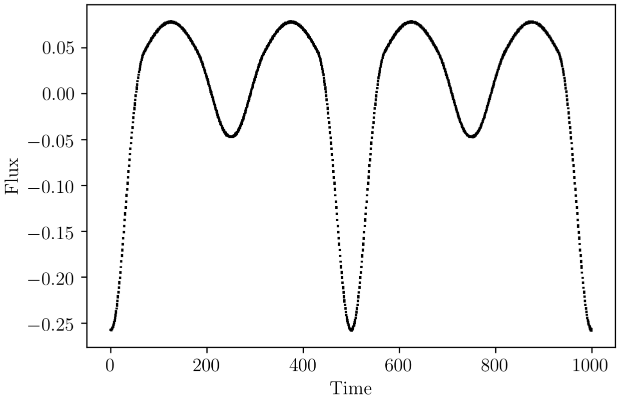

FIG. 4.— Example of an `ellc` generated light curve for an eclipsing binary system with masses $m_1 = 0.5M_\odot$ and $m_2 = 0.25M_\odot$, relative radii to the semi-major axis $r_1 = R_1/a = 0.5$ and $r_2 = R_2/a = 0.25$, inclination $i = 75°$, and period $P = 500$ s.

2.2. *Spectroscopy*

If my observing proposal is accepted, I plan to use the Double Spectrograph (DBSP) on Palomar's 200 inch telescope to observe one or two UCBs and analyze and model their spectra. As detailed in Burdge et al. (2019), we have period searched light curves taken with the Zwicky Transient Facility (ZTF), cross matched candidates to stellar catalogs such as the Roentgen Satellite (ROSAT) X-ray archive, and after visual scans are following-up on interesting targets to confirm real UCBs with the Kitt Peak Electron Multiplying CCD (KPED). With additional follow-up through DBSP phase-resolved spectroscopy, I will measure the radial velocities and masses of the binary objects as well as analyze properties of the individual objects and the system. I will fit the spectra just after the primary eclipse to stellar models, which isolates the primary object's spectrum and allows us to measure properties including effective temperature and surface gravity. Spectroscopic data can also reveal details about the system such as the presence of mass transfer or accretion, as detailed in Figure 5 from Burdge et al. (2019) With 2-4 hours of observation time, I will be able to observe multiple full periods of 1-2 systems. As UCB components are stellar remnants, P200's large 5 m mirror is well-suited to observing these faint objects. The targets are local, Galactic objects rich in H and/or He, and feature prominent spectral lines in the optical regime which are easily observable with DBSP.

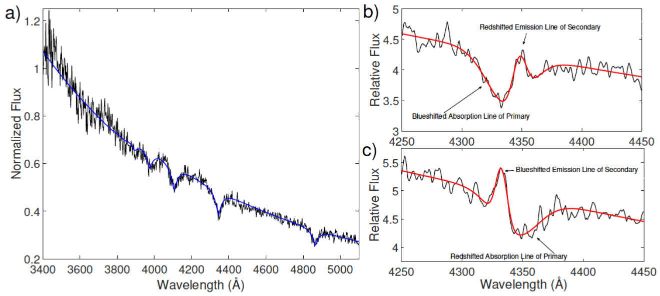

Fig. 5.— Spectroscopy of ZTF J153932.16+502738.8 from Burdge et al. (2019) taken with LRIS. a) shows the spectrum immediately after the primary eclipse, which isolates the primary object, and the best fitting stellar model (blue line). b) and c) show phase resolved spectra of the hydrogen n = 5 to n = 2 transition at 4340 Å, which lies within the DBSP wavelength range.

Coughlin et al. (2019) describe a DWD observed with DBSP. The binary system is ~ 18th magnitude, and is a double lined spectroscopic binary with a 40.6 minute period. The time series spectroscopy was done in 360 second exposures on DBSP, with the 600/4000 blue grating and a 1.5" slit which resulted in 1 Å resolution spanning 3400-5700 nm. With a similar observing protocol for 1-2 comparably bright targets with subhour periods, I expect to achieve a reasonable signal-to-noise ratio.

3. RESULTS

Depending on the incoming data from O3 and ZTF, I will to analyze light curves of transient and/or periodic binary stellar remnants. I expect to have results on the properties of these sources such as period, mass ratio, relative radii, and radial velocity semi-amplitudes. I hope to find and characterize interesting UCBs, such as DWDs or low mass X-ray binaries, from the catalog of ZTF light curves.

4. DISCUSSION

Some challenges I expect will arise include managing the large number of light curves collected by ZTF and including the orbital decay, $\dot{P}$, in our period search algorithms.

5. CONCLUSION

Multi-messenger astrophysics provides a new look at the Universe, allowing us to use more familiar EM observations to further constrain parameters about the properties of compact binaries observed with GW detectors. Using instruments including ZTF, KPED, and DBSP, we will observe these GW sources and analyze their light curves and spectra to better understand the astrophysics behind these multi-messenger events.

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