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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 emit both gravitational and electromagnetic 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 (UCB) systems, as will be detected by LISA. Using instruments including Palomar Observatory's Zwicky Transient Facility and Triple Spectrograph, and Kitt Peak's Electron Multiplying CCD, we observe and analyze light curves and spectra of these UCBs. With collaborators at Northwestern University, we also generate a catalog of gravitational-waveforms for compact white dwarf binaries in decaying orbits informed by Galactic binary population models, and simulate their light curves. These simulations help constrain the range of UCBs we expect to detect with future time domain surveys and follow-up observations.

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 Laser Interferometric Gravitational-Wave Observatory (LIGO) (LIGO Scientific Collaboration 2009), 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).

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. (2018a). 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. 2018b), 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.

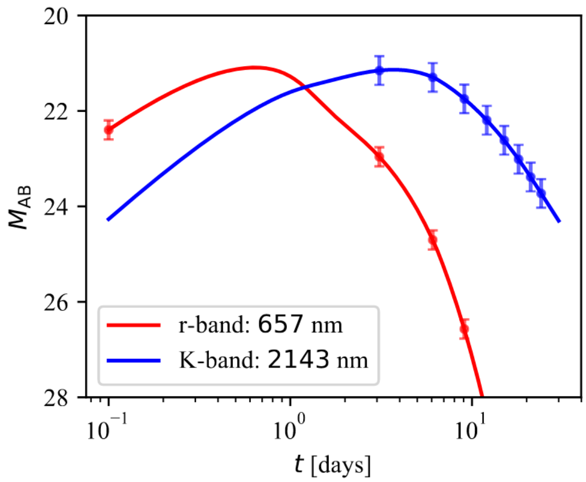

Figure 1. Mock light curve of a transient object from Barbieri et al. (2019) showing the characteristic nonperiodic brightening and extreme dimming over time.

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 Zwicky Transient Facility (ZTF) wide field camera (Graham et al. 2019) and the Dark Energy Camera (DECam) (Flaugher et al. 2015). 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 & van Haaften 2013). UCBs provide insight into many poorly understood stellar processes including common-envelope evolution, magnetic braking, and massive star evolution (Nelemans & van Haaften 2013).

UCBs also emit GW strongly in the low frequency regime which the future space based GW detector, LISA, is highly sensitive to (Nelemans & 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[1] 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. 2012a).

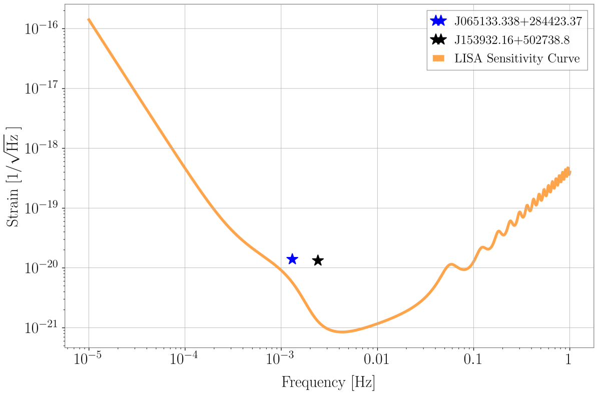

Figure 2. Amplitude spectral diagram for LISA showing the expected sensitivity (strain) of the detector at a given frequency. The blue and black points show estimated GW strain of two known UCBs, J065133.338+284423.37, a 12.75 minute period detached white dwarf binary (Hermes et al. 2012), and J153932.16+502738.8,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

One type of UCB, double white dwarfs (DWDs) are very common in our Galaxy as the majority of stars evolve into white dwarfs (Korol et al. 2017). We can characterize DWDs as detached by eclipses in their light

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[1] https://github.com/eXtremeGravityInstitute/LISA_Sensitivity

curve or semi-detached (AM CVn) by accretion features and He lines in their spectra (Nissanke et al. 2012b). The merger of DWDs may be progenitors to rare massive white dwarfs, solo neutron stars, subdwarf-O stars, or R Corona Borealis stars (Nissanke et al. 2012b). DWDs in a subhour binary can also help us study tides, white dwarf internal characteristics, and white dwarf viscosity (Korol et al. 2017).

Another type of UCB is the low-mass X-ray binary (LMXB). X-ray binaries in general are comprised of a massive stellar remnant, either a neutron star or stellar mass black hole, and a companion star, which is usually a main sequence star. The compact object accretes material from the companion star, creating a signature in the X-ray regime. These systems are useful for studying the evolution of massive stars in a binary system and to constrain the physics of core collapse (Type Ibc and Type II) supernovae (Casares et al. 2017). X-ray binaries with a $\leq 1\ M_{\odot}$ Roche-lobe filling companion star are further classified as LMXB. The objects in LMXBs corotate in circular orbits (Casares et al. 2017) with short periods on the order of hours. While some systems are eclipsing, non-eclipsing LMXB can also be analyzed if they feature ellipsoidal modulation. As it interacts with its compact companion via Roche lobe, the main sequence star becomes distorted, which causes the projected area of the star to vary as it orbits. This produces a characteristic double-humped, sinusoidal light curve (Charles & Coe 2003).

Verification binaries are located in our own Milky Way Galaxy, therefore, their surface density in the sky should peak near the Galactic Plane. LMXBs in particular are typically located in the Galactic bulge and in globular clusters (Casares et al. 2017). 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. However, 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. Half of LMXBs are found within 20 degrees of the center of the galaxy, which makes these systems significantly obscured in the optical regime (Charles & Coe 2003). As for detached DWDs, only 10s of objects 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.

Not every varying light curve, however, will correspond to an eclipsing binary source. The sample will be contaminated with pulsating white dwarfs, Delta Scuti variables, SX Phoenicis stars, and cool spots on the stellar surfaces coming in and out of view as the star rotates (Korol et al. 2017). 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.

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, we will be observing the localization region determined by LIGO and Virgo observations and GRB Fermi satellite detections with ZTF, DECam, and other instruments in the hours and days following the GW detection.

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 am 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 catalogs such as the Roentgen Satellite (ROSAT) X-ray archive (Voges et al. 1998), and after visual scans are following-up on interesting targets to confirm real UCBs with the Kitt Peak Electron Multiplying CCD (KPED) (Coughlin et al. 2019a). I am 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).

Similarly to Burdge et al. (2019), with high cadence 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.

2.2. *Spectroscopy*

In addition to high cadence photometry, we can follow up potential UCBs with phase-resolved spectroscopy.

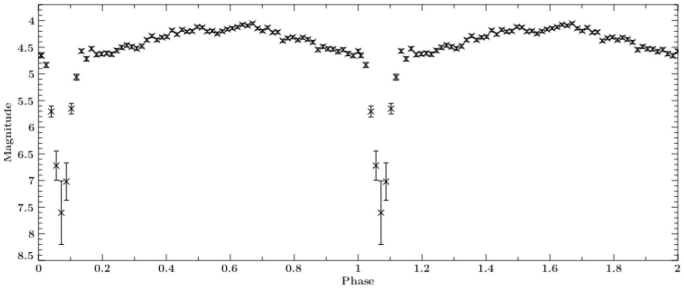

Figure 3. Phase folded light curve for the 7 minute period compact white dwarf binary system ZTF J153932.16+502738.8 from Kitt Peak's Electron Multiplying CCD (Coughlin 2019).

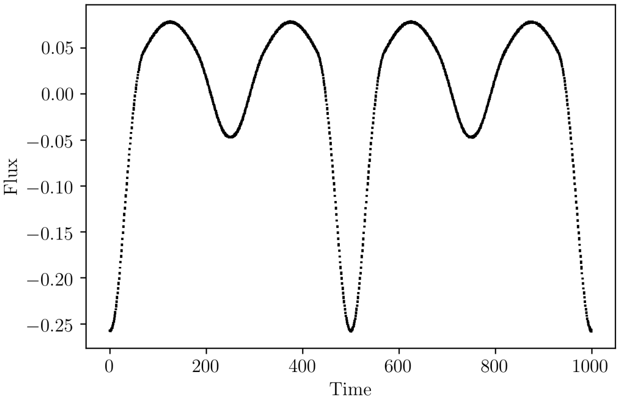

Figure 4. Example of an `ellc` generated light curve for an eclisping binary system with masses $m_1 = 0.5M_\odot$ and $m_2 = 0.25M_\odot$, relative radii to the semi-major axis $r_1 = R_1/a = 0.5$ and $r_2 = R_2/a = 0.25$, inclination $i = 75^\circ$, and period $P = 500$ s.

From these spectra, 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).

2.3. *Simulations*

According to general relativity, the orbital evolution of UCBs with characteristically short periods is primarily driven by GW radiation (Nelemans & van Haaften

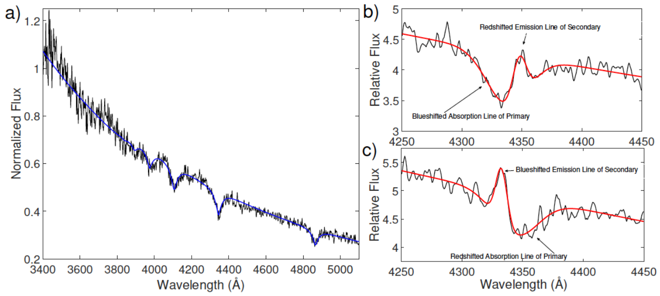

Figure 5. Spectroscopy of ZTF J153932.16+502738.8 from Burdge et al. (2019) taken with LRIS. a) shows the spectrum immediately after the primary eclipse, which isolates the primary object, and the best fitting stellar model (blue line). b) and c) show phase resolved spectra of the hydrogen n = 5 to n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

2013). This orbital decay mainfests in a decreasing period over time, given by

$$\dot{P} = -\frac{96\pi}{5c^5}(G\pi M_c f_{gw})^{\frac{5}{3}} \tag{1}$$

where M_c is the chirp mass ($M_c = (\mu^3 M_{total}^2)^{\frac{1}{5}}$) and f_{gw} is the gravitational-wave frequency ($f_{gw} = \frac{2}{P_{orb}}$).

To simulate light curves with orbital decay, I used the `ellc` package (Maxted 2016) to create eclipsing binary light curves with a constantly changing period. I wrote a python script that generates a light curve for a new period at each observation time given by

$$P_{new}(t) = P_0 + \dot{P} * t \tag{2}$$

where P_0 is the starting period and $\dot{P}$ is the rate of orbital decay in units of time/time. General relativity predicts that a typical DWD system with M_c on the order of 0.5 $M_\odot$ and a subhour period will have a $\dot{P}$ on the order of -10^{11} s/s. To construct a single output light curve for the series of light curves with decreasing periods, I computed the modulated time for each observation time and corresponding P_{new}, and interpolated the individual light curves at the modulus time for each P_{new}. This process returns a single light curve for a given set of binary parameters (including but not limited to mass ratio, inclination, and period) and a rate of orbital decay.

To simulate realistic time sampling, I generated time arrays of length n with Δt between each consequent observation point sampled by a random Gaussian distribution with mean Δt set appropriately according to which survey is being simulated. For ZTF, we expect a 1 year baseline with approximately 3 days between each observation (Bellm et al. 2019), so time sampling parameters were set to $n = 100$ and $\Delta t = 3$. To simulate LSST data, we expect a 10 year baseline with a larger Δt of around 1 week (Ivezić et al. 2019), so time sampling parameters were set to $n = 500$ and $\Delta t = 7$.

Together with a group of researchers at Northwestern University working on LISA science, we are using simulations to constrain the range of DWD systems we will be able to observe with current and upcoming long baseline time domain surveys using ZTF and the Large Synoptic Survey Telescope (LSST) (Ivezić et al. 2019). Our collaborators are putting together a simulated waveform catalog of WD binaries using the `COSMIC` package (Breivik 2018). `COSMIC` is a package that quickly synthesizes realistic Milky Way compact binary populations. From this binary population catalog, which will target the white dwarf binary population in the Milky Way, we can use the $\dot{P}$ light curve simulating script to generate light curves corresponding to the DWD waveforms.

3. RESULTS

3.1. *Observations*

I conducted visual scans of ZTF light curves to search for potential UCBs based on criteria informed by the astrophysics of DWDs and LMXBs. Our period search pipeline, beyond phase folding the time domain flux data using Conditional Entropy techniques, uses magnitude and color information to plot each object on an HR diagram. From there, I primarily searched white dwarf light curves for eclipses (see Figure 3 for an example) and periods on the order of minutes to an hour. Additionally, I searched the main sequence sources' light curves for ellipsoidal modulation with differential minima rather than maxima, which would indicate a contact binary instead of LMXB. Another criteria I included was the period, as we expect LMXBs that emit GW in the LISA regime to have periods on the order of hours.

After identifying a sample of interesting light curves, I cross checked the coordinates of the objects in SIMBAD to eliminate known sources. A number of known systems were eclipsing contact binaries, which are stars in such a close binary that the stars are touching or partially merged. A few sources were classified as AM Her type stars (see Figure 6), which are cataclysmic variables–a white dwarf and red dwarf in a close binary–where the white dwarf has a strong magnetic field, and although it has no accretion disk, features an extra long mass transfer stream or accretion column directed along the magnetic field lines straight onto the magnetic poles of the white dwarf. While these systems are interesting in their own right, as they are already identified, I eliminated them from my search to narrow down the pool of unknown sources which could be verification binaries.

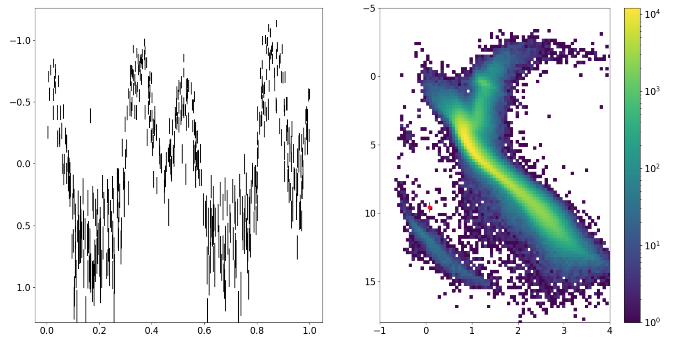

Figure 6. Phase folded ZTF light curve of V* EK UMa, a cataclysmic variable star of AM Her type.

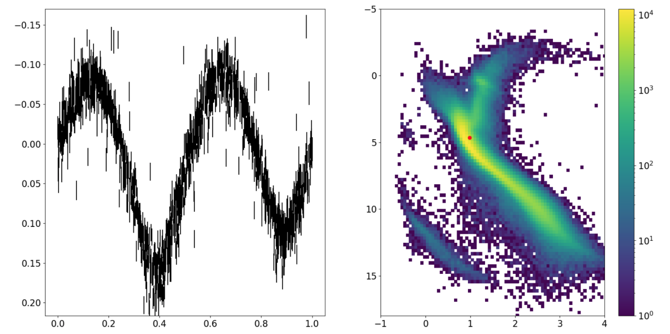

Figure 7. Phase folded ZTF light curve and HR diagram for ZTFJ1813694. With main sequence classification and differential minima without clear differential maxima, as well as high significance from the period finding algorithm, it may be a LMXB.

In total, I collected 10 LMXB candidate light curves, one of which is shown in Figure 7.

I hope to use KPED remotely to take high cadence photometric data of one or more of the UCB candidates I have identified from the ZTF search. For subhour period targets, I plan to take an hour of data in video mode with 10 second frames and 2 by 2 binning. Figure 8 shows the airmass curves for a sample of interesting targets to follow up on with KPED.

Since the first interim report, my SURF observing proposal has been accepted. On August 13th, I will use the Triple Spectrograph (TSpec), a near infrared spectrograph on Palomar's 200 inch telescope to observe a few potential UCBs which are on the main sequence and demonstrate possible ellipsoidal modulation. With TSpec phase-resolved spectroscopy, I will analyze and model their spectra to measure the radial velocities and masses of the binary objects as well as analyze properties of the individual objects and the system. Figure 9 shows the airmass curves for a these LMXB candidates on the night of the SURF P200 observing run.

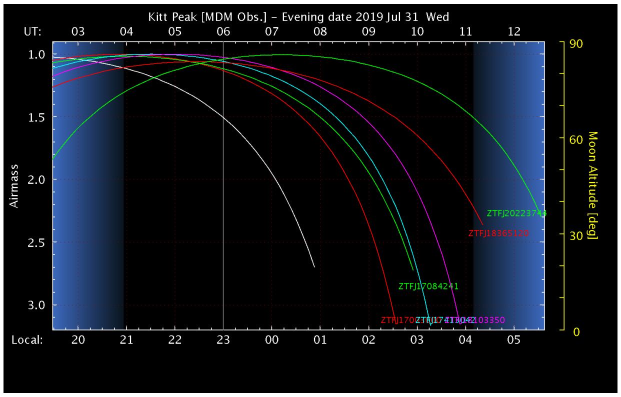

Figure 8. Air mass plot of a sample of targets I plan to observe remotely with KPED.

With 2 hours of observation time, I will be able to observe multiple phases of orbit for a few objects. Coughlin et al. (2019b) describe a DWD observed with a similar instrument to TSpec on the P200 telescope, the Double Spectrograph (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 3-5 comparably bright targets, I expect to achieve a reasonable signal-to-noise ratio.

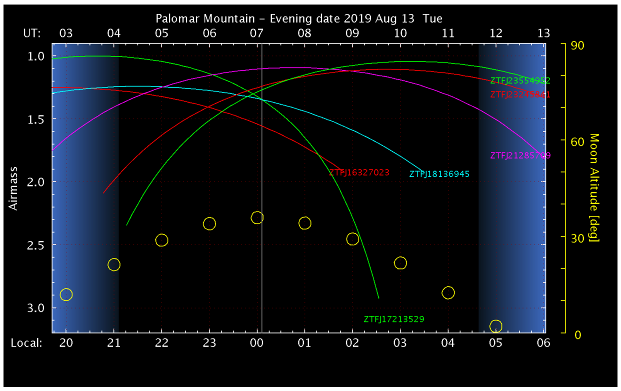

Figure 9. Air mass plot of a sample of targets I plan to observe with TSpec during the SURF observing run to Palomar Observatory on August 13th.

3.2. *Simulations*

With the $\dot{P}$ light curve simulating script, I have generated UCB light curves with orbital decay. Figure 10 illustrates the script output for a binary system with properties comparable to the DWDs studied in Hermes et al. (2012) and Burdge et al. (2019), but with a much greater $\dot{P}$ than is astrophysically plausible for better visibility. In this example, deviation from mid eclipse point for a system with no orbital decay is clearly visible.

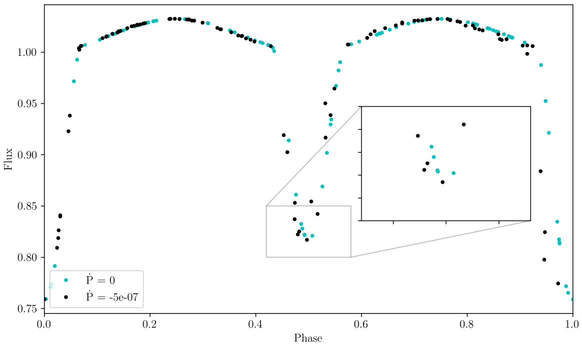

Figure 10. Example of a phase folded $\dot{P}$ light curve for an eclipsing system with exaggerated orbital decay. The turquoise points correspond to the case where $\dot{P} = 0$, and the black points simulate a system for which $\dot{P} = -5 * 10^{-7}$.

4. DISCUSSION

Throughout the next few weeks, I hope to collect some photometric and spectroscopic data of candidate UCBs that I have selected by scanning the phase folded ZTF light curves. So far, stormy weather in Tucson has hindered our ability to collect data using KPED.

On the simulation side, along with our collaborators at Northwestern, we are going to use the $\dot{P}$ light curve script and Galactic binary population simulation to quantify the DWDs we expect to be able to observe. In the more proximate future, I plan to generate simulated $\dot{P}$ light curves spanning inclination and period space and using our period finding script to get a sense for the approximate inclination and period range we are able to measure, down to a minimum significance value of ∼7-8.

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 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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REFERENCES

Barbieri, C., Salafia, O. S., Perego, A., Colpi, M., & Ghirlanda, G. 2019, arXiv e-prints, arXiv:1903.04543. https://arxiv.org/abs/1903.04543

Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019, PASP, 131, 018002, doi: 10.1088/1538-3873/aaecbe

Breivik, K. 2018, PhD thesis, Northwestern University

Burdge, K. B., Coughlin, M. W., Fuller, J., et al. 2019, Nature, 571, 528, doi: 10.1038/s41586-019-1403-0.

Casares, J., Jonker, P. G., & Israelian, G. 2017, X-Ray Binaries, 1499, doi: 10.1007/978-3-319-21846-5_111

Charles, P. A., & Coe, M. J. 2003, arXiv e-prints, astro. https://arxiv.org/abs/astro-ph/0308020

Coughlin, M. W. 2019, Before and after merger: Multi-messenger searches for compact binaries. https://physics.columbia.edu/files/physics/content/Coughlin.pdf

Coughlin, M. W., Dietrich, T., Margalit, B., & Metzger, B. D. 2018a, arXiv e-prints, arXiv:1812.04803. https://arxiv.org/abs/1812.04803

Coughlin, M. W., Dietrich, T., Doctor, Z., et al. 2018b, MNRAS, 480, 3871, doi: 10.1093/mnras/sty2174

Coughlin, M. W., Dekany, R. G., Duev, D. A., et al. 2019a, MNRAS, 485, 1412, doi: 10.1093/mnras/stz497

Coughlin, M. W., Burdge, K., van Roestel, J., et al. 2019b

Flaugher, B., Diehl, H. T., Honscheid, K., et al. 2015, AJ, 150, 150, doi: 10.1088/0004-6256/150/5/150

Graham, M. J., Kulkarni, S. R., Bellm, E. C., et al. 2019, PASP, 131, 078001, doi: 10.1088/1538-3873/ab006c

Hermes, J. J., Kilic, M., Brown, W. R., et al. 2012, ApJL, 757, L21, doi: 10.1088/2041-8205/757/2/L21

Hotokezaka, K., Nakar, E., Gottlieb, O., et al. 2018, arXiv e-prints, arXiv:1806.10596. https://arxiv.org/abs/1806.10596

Ivezić, Ž., Kahn, S. M., Tyson, J. A., et al. 2019, ApJ, 873, 111, doi: 10.3847/1538-4357/ab042c

Korol, V., Rossi, E. M., Groot, P. J., et al. 2017, MNRAS, 470, 1894, doi: 10.1093/mnras/stx1285

Kupfer, T., Korol, V., Shah, S., et al. 2018, MNRAS, 480, 302, doi: 10.1093/mnras/sty1545

LIGO Scientific Collaboration. 2009, Reports on Progress in Physics, 72, 076901, doi: 10.1088/0034-4885/72/7/076901

Maxted, P. F. L. 2016, ellc: Light curve model for eclipsing binary stars and transiting exoplanets. http://ascl.net/1603.016

Nelemans, G., & van Haaften, L. 2013, in Astronomical Society of the Pacific Conference Series, Vol. 470, 370 Years of Astronomy in Utrecht, ed. G. Pugliese, A. de Koter, & M. Wijburg, 153. https://arxiv.org/abs/1302.0878

Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. 2004, MNRAS, 349, 181, doi: 10.1111/j.1365-2966.2004.07479.x

Nissanke, S., Vallisneri, M., Nelemans, G., & Prince, T. A. 2012a, ApJ, 758, 131, doi: 10.1088/0004-637X/758/2/131

—. 2012b, ApJ, 758, 131, doi: 10.1088/0004-637X/758/2/131

Prince, T. A., Burdge, K., Coughlin, M., et al. 2019, in AAS/High Energy Astrophysics Division, AAS/High Energy Astrophysics Division, 112.18

Robson, T., Cornish, N. J., & Liug, C. 2019, Classical and Quantum Gravity, 36, 105011, doi: 10.1088/1361-6382/ab1101

Rosswog, S., Sollerman, J., Feindt, U., et al. 2018, A&A, 615, A132, doi: 10.1051/0004-6361/201732117

Smartt, S. J., Chen, T. W., Jerkstrand, A., et al. 2017, Nature, 551, 75, doi: 10.1038/nature24303

Voges, W., Boller, T., Dennerl, K., et al. 1998, in Science with XMM, 38