High-CAPS: A High-CAdence Plane Survey with ZTF

ZTF white paper – Thomas Kupfer, Tom Prince, Paula Szkody, Eric Bellm, David Kaplan, Kevin Burdge, Jan van Roestel, Monika Soraisam, Lynne Hillenbrand

Ultra(compact) binaries are an unique class of binary systems with periods <few hours (detached or semi-detached), consisting of a white dwarf (WD)/neutron star (NS) primary and a (semi-)degenerate or main sequence secondary. The study of these binaries is important to our understanding of such diverse areas as supernova Ia progenitors, binary evolution and they are predicted to be the dominant Galactic gravitational wave sources in the *LISA* band.

- **Potential SN Ia progenitors:** Supernovae Ia (SN Ia) are the most important standard candles and used to study the expansion history of the universe and the nature of dark energy. Although there is general consensus that only the thermonuclear explosion of a white dwarf can explain the observed features of those events, much less is known about their progenitor systems. One proposed scenario is the merger and subsequent explosion of an ultracompact double white dwarf system (double degenerate model).
– How many potential SN Ia progenitors exist and what is their space density?
- **Binary evolution:** (Ultra)compact binaries are highly evolved stages of binary evolution. They underwent at least one common envelope (CE) phase - a phase where two stars temporarily orbit within a shared envelope (Ivanova et al. 2013). The CE phase is still poorly understood but occurs in all compact binaries. For extreme mass ratios the final merger of the two components is prevented, leading to a stable mass transferring ultracompact system (Marsh et al. 2004).
– What is the effect of the CE phase on the population of (ultra)compact binaries? What is the population of ultracompact binaries?
- **Gravitational wave emitters:** *eLISA* is a space-based GW detector acting at lower frequencies than *LIGO*. Ultracompact binaries are strong GW sources and will dominate the population of GW emitters in the *eLISA* band. Systems with P_{orb}<20 min will be the strongest *eLISA* sources and 'verification sources' after launch. Currently, we know of only a handful of these sources although hundreds are predicted by theory to be detectable in our Galaxy. We have to find the 'verification binaries' over the following years because only constant monitoring with a baseline of 10 - 15 years will allow a precise enough measurement of the change of the orbital period ($\dot{P}_{orb}$) which in combination with gravitational data (amplitude, $\dot{P}_{GW}$) will allow a test of predictions for the orbital decay caused by GW radiation and possible deviations.
– How many 'verification sources' exist and what is their expected GW strength detectable by *eLISA*?

To answer these questions a better understanding of the population of (ultra)compact binaries as well as strong constraints on the parameters of individual systems are required. This is the aim of this survey.

Current status of the field

Studies have been conducted almost exclusively at high Galactic latitudes, because previous large scale surveys (e.g. SDSS) avoided the Galactic Plane. Since (ultra)compact binaries are a Galactic population their surface densities will strongly peak near the Galactic Plane with a stellar density 1000 times larger compared to the Halo. However, at low Galactic latitudes the current number of surveys is limited. The Rapid Temporal Survey (RATS, Ramsay & Hakala, 2005) was a photometric survey covering a total of 46 deg^2. RATS could not identify an (ultra)compact binary due to the limited sky coverage. The OmegaWhite (OW) survey covers 400 deg^2. OW operations began 5 years ago and up to now, 204 deg^2 have been observed. So far OW identified a few interesting systems, including the most compact He-star binary with P_{orb} = 44.6min (OW J0741; Kupfer et al. in prep.). Both surveys used a similar strategy by observing fields at low Galactic latitudes for continuous 2-3 hrs with a cadence of $\sim$2min. Although these surveys found interesting objects and show the strategy works well to find short-period variables, neither of them has the sky coverage for a detailed population study of (ultra)compact binaries, which is the main goal of the proposed High-CAPS survey.

Proposed observations

*High-CAPS (**High-CA**dence **P**lane **S**urvey with ZTF):* The reason that previous synoptic surveys avoided the Plane is because the high stellar density of the Plane places a huge burden on data analysis and storage. Fortunately, the development of the PSF-fitting image differencing pipeline PTFIDE, proven on Galactic Plane observations with PTF, allows extraction of variable stars in dense fields (Fig. 1).

To discover an unbiased sample of (ultra)compact binaries and study their population, we propose a high-cadence survey in the Galactic Plane ($|b| < 7^\circ$) covering the full inner Plane visible from the northern hemisphere (Galactic longitude $20^\circ < l < 230^\circ$) as part of the ZTF partnership time. This results in a total coverage of 2940 deg^2 which is more than 10 times larger than the current coverage of OmegaWhite. We propose to obtain 3 hr continuous lightcurves of each field with a cadence of 40 sec resulting in a total of $\approx$190 hrs of observing time to complete the survey. The baseline and the cadence will allow us to identify variability from 3 hr down to 2 min. The latter is the shortest period an ultracompact binary can have before merging. Observations should be conducted in $g\prime$ band because most of these objects have blue colors. Scheduling of individual fields is flexible with the only constraint that a field is visible and observed for at least 3 hours continuously.

(Ultra)compact binaries show up in lightcurves with variations on timescales of the orbital period (e.g. due to eclipses or tidal deformation of the components, see Fig. 2). We will search for and identify the most compact binary systems in the High-CAPS survey. We will study their population as well as individual systems in detail (e.g. orbital periods, $\dot{P}$ and masses). Additionally, we expect to identify a large number of fast transients.

Population study: The population of (ultra)compact binaries will mainly consist of double white dwarfs (DWD), semi-degenerate low mass helium stars (sdB/sdO stars) with WD companions and compact cataclysmic variables (CVs), late main sequence or L dwarfs with a WD accretor. A small fraction of neutron stars (NS) with white dwarf, helium star or main sequence companions are also expected.

- **Cataclysmic variables:** CVs should be the most numerous of the ultracompact binaries found in the survey, as they are 100 times more numerous than DWD binaries. The SDSS survey estimated a space density of 0.03 deg^2 down to an i magnitude of 19 (Szkody et al. 2004), so 5,000-10,000 are expected to be in ZTF. Population models as a function of orbital period (Goliasch & Nelson 2015) predict the majority of systems should be near orbital periods of about 80 min. At this period, the systems would have an absolute magnitude of 11.6 (Gänsicke et al. 2009). The high cadence observations will cover 2-3 orbital periods which is needed to find the orbital period precisely. Past SDSS followup work has shown that about 40% of disk CVs show their orbital periods due to the presence of a hot spot on the disk or eclipses (with the largest amplitude modulations present in the bluest filters). CVs containing highly magnetic white dwarfs (polars and intermediate polars), which comprise 20% of CVs, all show orbital modulations due to views of the accretion columns. Knowledge of the orbital periods then provides a critical test of the evolution of the evolution models for close binaries

- **Double white dwarfs:** Based on binary population studies from Nelemans et al. (2001) the merger rate of DWD binaries in the Galactic Plane is $1.1 \times 10^{-2}\,\mathrm{yr}^{-1}$. The limiting magnitude of ZTF is 20.4 mag which will allow us to detect DWDs up to a distance of 1.3 kpc (for an absolute magnitude of 10 mag and no dust extinction). With the merger rate and the observable volume, we expect to find about 110 new DWD systems with $P_{\mathrm{orb}} < 60$ min in the High-CAPS survey (8 systems with $P_{\mathrm{orb}} < 20$ min and even 700 with $P_{\mathrm{orb}} < 2$ hr).
DWDs are SN Ia progenitors through the double degenerate model. Currently only one known system is believed to merge within a Hubble time and explode as a SN Ia.

- **Low mass helium stars (sdB/sdO stars):** To estimate the number of detectable ultracompact sdB/sdO binaries in the High-CAPS survey we take the birthrate of ultracompact sdB/sdO stars with WD companions from Han et al. (2003) which is $\sim 10^{-3}\,\mathrm{yr}^{-1}$. We will be able to detect sdB/sdO binaries up to a distance of 10 kpc (for an absolute magnitude of 4.5 mag and 1 mag dust extinction). Therefore, we expect to find about 10-15 new (ultra)compact sdB/sdO binaries with WD companions and orbital periods $P_{\mathrm{orb}} \leq 60$ min in the High-CAPS survey. This is consistent with OmegaWhite which found one system but covers less than 1/15 of the sky area of High-CAPS. Additionally, we expect to find about 30 systems with $P_{\mathrm{orb}} < 2$ hr.
sdB/sdO stars are SN Ia progenitors through the double detonation model and possibly SN .Ia progenitors if the WD companion mass is small. Currently, only one progenitor for the double detonation scenario is known.

- **Neutron stars with WD/sdB/sdO companions:** Nelemans et al. (2001) found a merger rate of $1.4 \times 10^{-4}\,\mathrm{yr}^{-1}$ which is about a factor of 100 smaller compared to DWDs. Therefore, we expect to find probably 1-2 ultracompact NS+WD binaries and 1 ultracompact NS+sdB/sdO binary in the High-CAPS survey. Although this number is too small for a population, the discovery of such a system would be unique on its own.
NS+sdB/sdO/WD mergers are believed to produce calcium-rich transients. However, no progenitor of a calcium-rich transient is known today.

- **Fast Transients:** Slow mass-accreting WDs that are massive, near the Chandrasekhar limit, are theoretically predicted to show rapidly declining nova explosions with expected timescales as short as few hours. Observing them, and potentially, constraining their populations are important in the context of SN Ia progenitor scenario. As the WDs in the Galactic Plane result from young stellar population, they are relatively massive.

The targeted field and cadence of High-CAPS is thus well-suited for very fast novae.

Target selection: We will extract variable objects from the difference images and from previous experience (e.g. MacFarlane et al. 2015) we expect to find $>10^6$ variable sources. The majority of those will be typical pulsating stars like Delta Scuti pulsators. The key will be to find the needle in the haystack and select the (ultra)compact systems from the bulk of pulsating stars. A combination of color-selection and proper motions will allow us to distinguish between the bulk of pulsators with potential (ultra)compact binaries, e.g. DWDs, CVs and sdB/sdO stars populate different parts of the color-color diagram and have higher proper motions than typical pulsators like Delta Scuti stars with similar magnitudes.

· **Color selection:** Color selection will be done using EGAPS, Pan-STARRS as well as Galex, Fermi and VLASS. Pan-STARRS DR1 has released static colors in g, r, i, z and y for the full northern hemisphere, including the Galactic Plane in December 2016. EGAPS will provide color information in u,g,r,i and Hα for the full northern Plane with $|b| < 5°$.

· **Proper motions from Gaia DR2:** In the 2nd half of 2017 Gaia will release accurate proper motions for all stars (including the Galactic Plane) with single star behavior based on their astrometric solution. Because the components in ultracompact binaries are so close ($\leq 0.5\,R_\odot$), Gaia will treat them as single stars and therefore proper motions for ultracompact binaries will be part of DR2.

Individual study: Once interesting candidates are found, we will do a detailed follow-up study to confirm their nature and study individual system parameters making use of different facilities.

Candidate (ultra)compact binaries selected from the High-CAPS survey will be scheduled for low resolution spectroscopic follow up, during which we will take two consecutive spectra and search for large radial velocity variations ($>100\,\mathrm{km\,s^{-1}}$) on timescales of a few minutes (see Fig. 3). This work can be done with the Palomar 200-inch and the APO 3.5-meter telescope. The most interesting systems, e.g. with the highest radial velocity variations and short photometric variations, will be selected for follow up phase-resolved spectroscopy using medium resolution spectroscopy. To obtain a high accuracy radial velocity curve from spectra with sufficient SNR within short exposure times, 8m class telescopes like Keck and Gemini are needed in most cases. A few nights each semester on each telescope are sufficient.

The big picture

With the large number (≈several hundred) of expected systems discovered by the High-CAPS survey, we will derive, for the first time, an empirical space density for different types of ultracompact binaries in the Galaxy. The space density, together with the mass and orbital period distribution will allow us to calculate empirical SN Ia rates for different supernova channels on a significant statistical sample. The expected large sample will challenge common envelope and binary evolution theories, e.g. predicted vs. observed orbital period and component mass distributions. Accurate component masses and orbital periods of individual systems will allow us to predict the expected GW strength detectable by *eLISA*.

Expertise to undertake project

Variable objects are extracted from the ZTF difference imaging pipeline which removes all non-variable objects. Once the locations of the different candidate sources are identified, we proceed to construct their lightcurves using the whole set of difference images per candidate. We perform forced photometry at these positions. As we are measuring fluxes on difference images, which are relatively sparsely populated and stellar blending is not expected even in a high density region like the Galactic Plane (see Fig. 1). We have developed all the tools needed and tested on M31 and Galactic plane iPTF fields (e.g. Soraisam et al. 2017).

Manpower and time line

Thomas Kupfer (PI) will lead the project and overlook the progress of the project. Caltech graduate student Kevin Burdge will search for ultracompact binaries and conduct a population study as part of his PhD thesis under guidance of Thomas Kupfer and Tom Prince. Paula Szkody will work on identification and population study of cataclysmic variables discovered in the survey. David Kaplan and Eric Bellm will lead the work on potential neutron star binaries found in the survey. Jan van Roestel and Monika Soraisam will lead the effort to search for fast transients in High-CAPS.

The first few months of the survey will be used to optimize the selection methods to extract candidates from High-CAPS. From the start of the survey, we will identify and follow-up individual systems which will result in subsequent publications over the full course of the survey. Once the survey is completed we will conduct a detailed study of the population of ultracompact binaries to put constraints on the number of SN Ia progenitors, 'verification sources' and the expected Galactic background for *eLISA*.

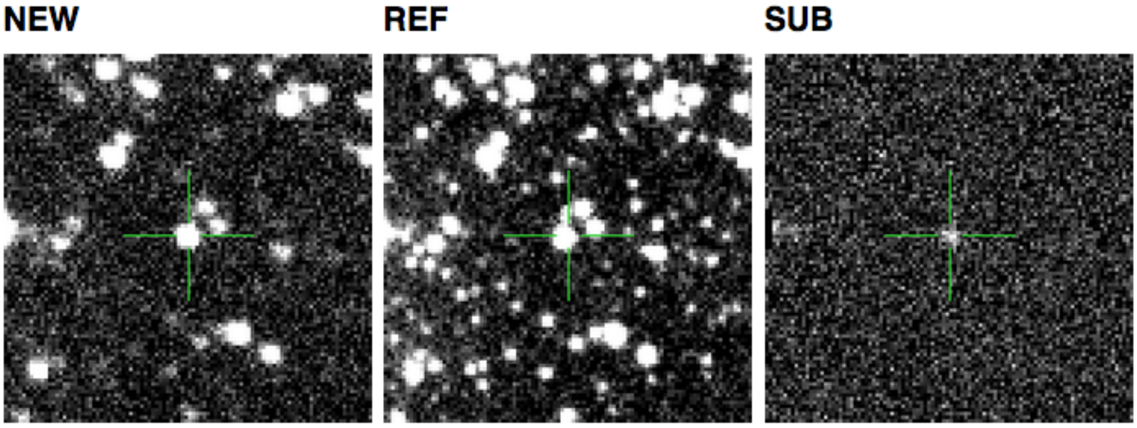

Figure 1: **Left panel:** Cut-out region of a science image obtained in the Galactic Plane using the PTF camera which has the same resolution as the ZTF camera, **Middle panel:** Reference image of the same field, **Right panel:** Difference image of the same field where only the variable source is left. Image subtraction with a reference image allows to identify variable objects even in crowded fields.

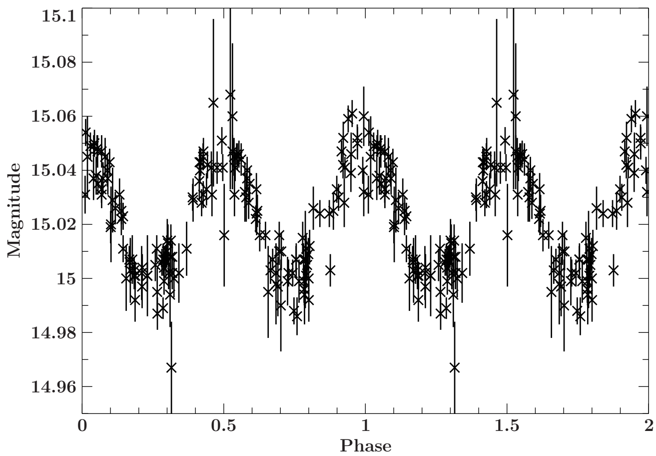

Figure 2: Phase folded lightcurve of the 87.5 min period ultracompact sdB binary found by the Palomar transient factory. The variability in the lightcurve is caused by tidal deformation of the sdB star. The companion is a low-mass WD (Kupfer et al. 2017).

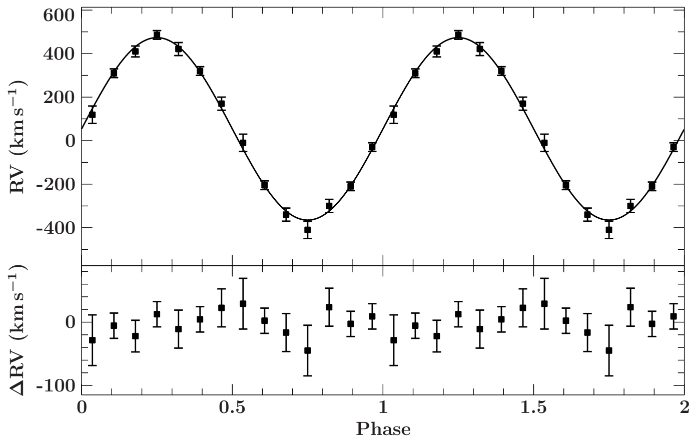

Figure 3: Preliminary radial velocity (RV) curve of OW J0741, an ultracompact He-star binary with $P_{\rm orb}$=44.6 min. The companion is most likely a massive WD with $> 0.7\,M_\odot$ making the system a good candidate for a double detonation supernova Ia progenitor. The system was found and followed-up with the same strategy which we will use for High-CAPS. (Kupfer et al. in prep).

References:

Gänsicke, B. T. et al. 2009, MNRAS, 397, 2170; Goliasch, J. and Nelson, L. 2015, ApJ, 809, 80; Han, Z. et al. 2003, MNRAS, 341, 669; Ivanova, N. G. et al. 2013, Science, 339, 433; Kupfer, T. et al. 2017, ApJ, 835, 131; Marsh, T. R. e al. 2004, MNRAS, 350, 113; Macfarlane, S. A. et al. 2015, MNRAS, 454, 507; Nelemans, G. et al. 2001, A&A, 375, 890; Ramsay, G. & Hakala, P. 2005, MNRAS, 360, 314; Szkody, P. et al. 2004, AJ, 128, 1882; Soraisam, M. D. et al. 2017, A&A in press