The Stellar Binary Survey

Eric Bellm, Thomas Kupfer, Adam Miller, and Tom Prince (Caltech)

Current and forthcoming variability surveys are identifying stellar binaries throughout the Galaxy with unprecedented sensitivity. Well-sampled optical lightcurves reveal orbital periods as well as characteristic lightcurve shapes that may be used to identify the most scientifically valuable binary subtypes with high purity.

We propose a Stellar Binary Survey (SBS) of photometrically-classified stellar binaries using the Sloan 2.5 m and the BOSS spectrographs with the following aims:

- Discovery of compact binaries through large radial-velocity (RV) shifts.
- Identification of eclipsing binary components through composite spectra.
- Expanding spectroscopically-identified training samples for LSST photometric classification.

Seed Surveys

ZTF The Zwicky Transient Facility [ZTF; 1] will provide more than 750 epochs in two colors across the entire Northern Sky upon the completion of its three-year survey in 2020. With median depths of $m_r = 20.5$, it will identify several million periodic sources well-matched to 2.5 m+BOSS followup. In particular, it will include extensive coverage of the Northern Galactic Plane, an area currently poorly covered by synoptic surveys. Observations of the Northern Plane offer an attractive niche for a future 2.5 m survey, as it lies outside of the DESI survey footprint.

PanSTARRS and *WISE* Color selection provides additional statistical leverage for identifying stellar binaries [e.g., 2]. With the availability of IR (WISE) and optical (PanSTARRS-1) catalogs over the entire Northern Sky, we can straightforwardly link colors to ZTF variability.

Gaia The *Gaia* mission will provide a wealth of data that will further improve our ability to select pure binary samples. From its photometry alone, *Gaia* will identify millions of periodic sources using about 80 epochs; its higher photometric precision will complement the lightcurve shape characterization provided by ZTF. *Gaia* distances and proper motions will pinpoint stellar populations. While *Gaia* will provide RV measurements for bright sources ($V \lesssim 15.5$ mag), newly acquired SDSS spectra can complete the 6D astrometric solution for fainter objects.

Efficient Discovery of Rare Compact Binaries

A small fraction of optically periodic systems ($\lesssim$1%) contain compact objects, and these are concentrated in the Galactic Plane. Typically these are white dwarf (WD)-main sequence (MS) binaries, but double WD binaries, WD + He star binaries, and quiescent Low-Mass X-ray Binaries with neutron-star or even black hole primaries lurk among these. In short period systems ($P_{\rm orb} \lesssim$ 1 day), ellipsoidal variations and reflection effects create lightcurve signatures that may be used in addition to color selection and/or X-ray cross-correlation to select compact binary candidates with high purity.

SBS spectroscopy will then confirm the presence of a compact object by identifying the large-amplitude radial-velocity shifts (hundreds of km/s). For the shortest period systems, 15-minute sub-frames of an hour-long pointing are sufficient to identify the shift [3]. For intermediate periods (a few hours to a day), a second epoch may be needed.

As these systems are intrinsically rare, a greatly-enlarged dynamically confirmed sample will enable a wide range of science, including measurements of neutron-star and black hole masses and clarification of binary evolution scenarios [4; 5].

Identifying Eclipsing Binary Components with Composite Spectra

Spectroscopy is necessary to identify the components of non-contact binaries, as color selection alone is insufficient due to blending. By targeting tens of thousands of photometrically-identified detached eclipsing binaries (EBs), we can systematically identify binary membership for a large, homogeneous sample. These binary demographics will constrain models of stellar and binary evolution.

Furthermore, SBS spectroscopy will identify the largest sample of double-lined EBs. Additional epochs of high precision spectroscopy with other facilities can then provide accurate component masses and radii for such systems. Only 184 systems have been well-characterized to date [6]. Of primary interest for followup will be the rare subtypes revealed by SBS spectra, such as high- and low- mass EBs and giant EBs [7, and references therein]. This program will naturally complement the *APOGEE* observations of 100 *Kepler* EBs, which have greater photometric precision but much less sensitivity to rare binary configurations.

Establishing the Spectroscopic Ground Truth for LSST Classifiers

As most LSST sources will be too faint for routine spectroscopy, photometric classifiers will be required in order to identify stellar populations. Photometry alone can separate many sub-types of periodic sources [8], but current catalogs have relatively little magnitude overlap with LSST, inhibiting direct transfer to the LSST data. In contrast, ZTF will have several magnitudes of overlap with LSST.

However, it will not be sufficient to train a classifier on ZTF and apply it to LSST, as major biases will result from the differences between the surveys [9]. Instead, we will build a large spectroscopic "ground truth" sample by selecting sources spanning the full diversity of ZTF periodic variability. By selecting sources with high-confidence classifications as well as those with uncertain predictions, we will ensure that future LSST-derived classifiers have the maximal information possible. By selecting these targets in the spatial region ($0^\circ > \delta > -30^\circ$) and magnitude range ($16 \lesssim m \lesssim 21$) that overlap LSST, we will maximize their value for building classifiers directly with LSST data.

Target Densities

The current Palomar Transient Factory (PTF) survey already provides a preview of the expected ZTF returns, with tens to a few hundreds of epochs in R band. By the time of a full proposal, we expect to have generated a periodic sources catalog for the complete PTF dataset that will guide our SBS fiber budget. As of this writing, the Catalina Real-Time Transient Survey (CRTS) Periodic Sources Catalog [10] provides the best guide at high Galactic latitudes. With worse photometric precision than PTF, CRTS found 61,000 periodic variables over 20,000 deg^2. However, the Bulge microlensing surveys OGLE and MACHO have identified hundreds of thousands of periodic objects at ZTF depths in just a few hundred deg^2. Accordingly, we expect ZTF to catalog several million periodic sources across the sky, including hundreds of thousands of detached EBs and tens of thousands of compact binary candidates.

While low Galactic latitude pointings will be more efficient, the relatively low areal densities of these source classes (e.g., $\sim$1 WD deg^{-2}) imply that these programs are best pursued as ancillary science. Allocations of tens of thousands of fiber-hours for the compact object and EB programs would provide unprecedented samples of previously rare objects, while even a few thousand fiber-hours would bootstrap future LSST classifiers.

[1] Bellm, E. (2014), in Wozniak, P. R., et al. (eds.), *The Third Hot-wiring the Transient Universe Workshop*, 27–33
[2] Palaversa, L., et al. (2013), AJ 146, 101
[3] Badenes, C., et al. (2009), ApJ 707, 971
[4] Schreiber, M. R. et al. (2003), A&A 406, 305
[5] Belczynski, K., et al. (2012), ApJ 757, 91
[6] Southworth, J. (2015), in Rucinski, S. M., et al. (eds.), *Living Together: Planets, Host Stars and Binaries*, *Astronomical Society of the Pacific Conference Series*, vol. 496, 164
[7] ——— (2012), in Arenou, F. et al. (eds.), *Orbital Couples: Pas de Deux in the Solar System and the Milky Way*, 51–58
[8] Richards, J. W., et al. (2012), ApJS 203, 32
[9] ——— (2012), ApJ 744, 192
[10] Drake, A. J., et al. (2014), ApJS 213, 9