PROSPECTS FOR DETECTING ASTEROSEISMIC BINARIES IN KEPLER DATA

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ABSTRACT

Asteroseismology may in principle be used to detect unresolved stellar binary systems comprised of solar-type stars and/or red giants. This novel method relies on the detection of the presence of two solar-like oscillation spectra in the frequency spectrum of a single light curve. Here, we make predictions of the numbers of systems that may be detectable in data already collected by the NASA Keplert Mission. Our predictions, which are based upon TRILEGAL and BiSEPS simulations of the Kepler field of view, indicate that as many as 200 or more “asteroseismic binaries” may be detectable in this manner. Most of these binaries should be comprised of two He-core-burning red giants. Owing largely to the limited numbers of targets with the requisite short-cadence Kepler data, we expect only a small number of detected binaries containing solar-type stars. The predicted yield of detections is sensitive to the assumed initial mass ratio distribution (IMRD) of the binary components and therefore represents a sensitive calibration of the much debated IMRD near mass ratio unity.

Key words: binaries: general – Galaxy: stellar content – stars: evolution – stars: statistics – surveys

Online-only material: color figures

1. INTRODUCTION

The NASA Kepler Mission has provided a wealth of data for studying stellar binary systems. More than 2000 eclipsing binaries have so far been found (Prša et al. 2011; Slawson et al. 2011). Circumbinary planets have also been discovered in several of these systems (e.g., see Welsh et al. 2012; Orosz et al. 2012). The Kepler eclipsing binary catalog\textsuperscript{6} provides information on binaries with periods up to a few hundred days. In this Letter we discuss the prospects for using asteroseismology as a novel way of discovering non-eclipsing binary systems in numbers that would potentially provide a useful statistical sample, out to periods much longer than the eclipsing binary catalog.

Asteroseismology has been one of the major successes of Kepler. It has in particular revolutionized the study of stars that show solar-like oscillations, with detections made in several hundred cool main-sequence and subgiant stars (Chaplin et al. 2011c, 2014), and over 10,000 red giants (e.g., see Bedding et al. 2011; Hekker et al. 2011; Huber et al. 2011, 2014). These stars present rich spectra of overtones in the frequency–power spectrum.

Asteroseismology may be used to discover candidate binaries by detecting the presence of two solar-like oscillation spectra in the frequency spectrum of a single Kepler light curve. The oscillation spectra may be well separated in frequency; or they may overlap, with the individual oscillation peaks of the two stars interspersed. To illustrate the concept, we have created an artificial example by using Kepler data on two red giants in the open cluster NGC 6819. We combined the light curves of two cluster members—KIC 5024405 and KIC 5112950—with detected oscillations (from Figure 2 of Stello et al. 2010). The bottom of our Figure 1 shows the frequency–power spectrum of the combined light curve (i.e., the simulated asteroseismic binary), while the upper two panels show the spectra of the two original light curves. Arrows mark the locations of the solar-like oscillations. The analysis required to discriminate the constituent oscillation frequencies of stars comprising asteroseismic binaries is beyond the intended scope of the present Letter, although we add that in some scenarios—when the oscillation spectra are well separated in frequency—it is a fairly trivial matter. That would have been the case for our artificial example: the oscillations are clearly separated (because KIC 5112950 is about 2.5 times more luminous than KIC 5024405).

Our aim in this Letter is to estimate—subject to different assumptions about the underlying binary population—the number of binaries in the Kepler field where both components would be expected to show detectable solar-like oscillations in Kepler data. Our results are based on predictions from two stellar population simulations of the Kepler field, to which we applied target selection criteria based on those used to select the real Kepler target list. We consider binaries comprised of solar-type stars and/or red giants. Imposing the seismic detectability constraint for both components strongly favors binaries with mass ratio near unity. The predicted number therefore represents a very sensitive calibration of the much debated initial mass ratio distribution (IMRD; e.g., Goodwin 2013 and references therein) near mass ratio unity.

The layout of our Letter is as follows. In Section 2 we discuss the population synthesis predictions made by TRILEGAL (Girardi et al. 2005, 2012; Section 2.1) and BiSEPS (Farmer et al. 2013; Section 2.2); and target selection applied to the raw predictions (Section 2.3). In Section 3 we explain how we used the data on the intrinsic properties of the synthetic target-selected populations to make the asteroseismic detection
predictions. Section 4 presents results on the asteroseismically detected synthetic binaries. We end in Section 5 with concluding remarks on the implications of our results for analysis and exploitation of the real, available Kepler data.

2. POPULATION SYNTHESIS PREDICTIONS

2.1. TRILEGAL

We used TRILEGAL (see Girardi et al. 2005, 2012 for a detailed description) to simulate the Milky Way. TRILEGAL comprises a geometric model for the principal components, e.g., the thin and thick disks, halo, and bulge, with constituent populations having a prescribed star formation rate and age–metallicity relation. The dimensions of the components were calibrated from selected real observations (e.g., where reddening is small and photometric incompleteness is not an issue). The implicit assumption is made that, aside from interstellar dust, the Galactic components are smoothly distributed, and uniform in their distributions of age and metallicity.

Standard parameters were used for each component of the Milky Way. Stellar populations were simulated for the fields covered by each of the 21 five-square-degree Kepler CCD pairs. Interstellar extinction was modeled at infinity (Schlegel et al. 1998), and assumed to arise from a dust layer having a 100 pc scale height. Stellar magnitudes were estimated in the Kepler bandpass using the known instrumental response function. To mimic the selection function used to compile the Kepler target list, the synthetic population was filtered using the procedure described below in Section 2.3.

Non-interacting binaries are included in the stellar populations simulated with TRILEGAL. For each star, there is a probability $f_b$ that it belongs to a binary system. The secondary star has the same age and metallicity as the primary, and its mass is drawn from a flat IMRD in the interval $[b_m, 1]$. Default values of $f_b$ and $b_m$ are 0.3 and 0.7, which we also adopt in our reference simulations.

2.2. BiSEPS

The BiSEPS code (see Willems & Kolb 2002, 2004; Willems et al. 2006; Farmer et al. 2013 for a detailed description) employs the semi-analytical description for single and binary star evolution by Hurley et al. (2000) and Hurley et al. (2002) to create a large library of evolutionary tracks. The resulting Galactic stellar population models therefore include evolving and interacting binaries in a self-consistent way. The evolutionary tracks are weighted according to initial distribution functions and convolved with a star formation history. We adopt canonical initial distribution functions for (primary) mass and orbital separation, while the secondary mass is selected from a power-law IMRD, $\chi(q) = (s + 1)q^s$, where $q$ is the initial mass ratio and $s$ is a free parameter. We consider simulations computed with $s = -0.5, 0, 1, 1$, assuming that 50% of all systems form as binaries.

To model the Kepler field content we take into account contributions by the thin disk and thick disk populations, adopting hydrogen abundance $X = 0.70$ for all stars and representative metallicities $Z = 0.02$ and $Z = 0.0033$, respectively. The extinction is calculated following Drimmel et al. (2003), with bolometric corrections and extinction coefficients taken from Girardi et al. (2008).

2.3. Target Selection

To model the impact that the Kepler target selection procedure has on the simulated binary sample we tested the synthetic Kepler field against the same criteria that were used to compile the actual Kepler target list from the Kepler Input Catalog (KIC). The rank-order is determined by the minimum detectable planet radius (neglecting intrinsic stellar noise) for observations lasting the full duration of the nominal Kepler mission.

The selection process involves the creation of synthetic full-frame images—which also include detector noise and zodiacal noise—to determine the optimum aperture that maximizes the signal-to-noise ratio for each target. The ranking is based on stellar parameters estimated from the synthetic colors of each target, following Kepler’s Stellar Classification Program (Brown et al. 2011). We modeled binaries as being comprised of two point sources, with effective magnitudes calculated from the summed fluxes of the stars in the considered wavelength band.

The BiSEPS model applies a set of color corrections to its synthetic stars to force better agreement with the actual KIC in color–color space; this step was not needed for the TRILEGAL model.

Full details of the target selection procedure are presented in Farmer et al. (2013).

3. PREDICTIONS OF ASTEROSEISMIC DETECTABILITY

We applied the procedure in Chaplin et al. (2011b) to every simulated star in the target-selected samples to predict whether
we would expect to make an asteroseismic detection. The procedure uses as input the fundamental properties of each modeled target—be it a single field star or both components of a binary—as well as the simulated Kepler apparent magnitude, and the assumed duration of the observations, to estimate what would be the observed photometric signal amplitude due to solar-like oscillations, granulation, and shot noise. From these estimates we may calculate the likelihood of making a robust detection of solar-like oscillations. As in Chaplin et al. (2011b), we flag a detection as made when the estimated probability of detection is higher than 90%.

We corrected the predicted amplitudes of the oscillations and granulation signals of targets in binaries to allow for the dilution of the observed signal due to the presence of the companion star. These corrections were made in the Kepler bandpass, using the bolometric corrections in Ballot et al. (2011).

We adopted two different assumed observation durations, depending on the type of target. The 58.85 s Kepler short-cadence (SC) data are needed to detect oscillations in cool main-sequence and subgiant stars, since the dominant oscillations have periods of the order of minutes. These short periods are not accessible to the 29.4 minute long-cadence (LC) data (for which the Nyquist frequency is \( \sim 283 \mu \text{Hz} \)). Due to the target-limited nature of the SC data, around 2000 targets were identified in the KIC as solar-type stars were observed for only one month at a time during the asteroseismic survey conducted in the first

**Figure 3.** Stacked histograms showing the evolutionary state of the secondary component of detectable seismic binaries as a function of the evolutionary state of the primary.

(A color version of this figure is available in the online journal.)
4. RESULTS

Figure 2 is a Hertzsprung–Russell diagram showing members of the target-selected TRILEGAL and BiSEPS samples with predicted asteroseismic detections. Results are shown from simulations in which the binary populations were given a flat IMRD. Gray stars (circles) mark cases where a detection was predicted for the more luminous component of a binary (a single field star). The colored symbols connected by solid lines mark cases where both components of a binary showed detectable solar-like oscillations.

Results given by the target-selected sample from the TRILEGAL population, having $f_b = 0.3$ and $b_b = 0.7$, predict that there will be around 200 detectable asteroseismic binaries in the Kepler LC data. This corresponds to just over 1% of the 20,000 red giants flagged as showing a seismic detection. Most of these asteroseismic binaries will be comprised of two stars in the He-core-burning, or red-clump, phase (see Figure 3). Similar results were returned by the BiSEPS population when an IMRD with exponent $s = 1$ was adopted. Absolute numbers drop to around 120 (60) when $s = 0$ ($s = -0.5$). The synthetic target-selected samples include a small fraction of binaries that are either in a phase of mass transfer or have undergone such a phase in the past. None of these objects are detectable as asteroseismic binaries. Only a handful of binaries will be detectable in the main-sequence and subgiant phase. This is due both to the restrictions on the number of suitable targets with the requisite SC data (see Section 3), and the lower observable asteroseismic signal-to-noise ratios in these stars, compared to red giants (which makes seismic detection of binaries much harder).

We may gain some insights on the likely robustness of the predicted absolute numbers of binary detections by comparing predicted numbers of individual detections with those already made from the Kepler data. The simulations predict detections in around 1500 main-sequence and subgiant stars (note we have compensated for the fact that the simulated target-selected
samples are around 20% larger than the real Kepler target sample. The predicted number of detections is approximately a factor of two higher than the number of recorded detections (Chaplin et al.
2011c; Verner et al. 2011; Huber et al. 2013). Some of this difference may be attributed to the restricted number of SC target slots that were available to the real asteroseismic survey, and the selection procedure for the asteroseismic targets (which we have not reproduced here). There will also be a contribution due to stellar magnetic activity, which reduces the detectability of the solar-like oscillations (Chaplin et al. 2011a). This is an effect we have not allowed for in our simulations. Our conclusions for the SC data will remain the same in spite of these differences: we expect very few seismic binary detections in SC.

The impact of activity will be much less important for the more evolved cohort of stars observed in LC, where the simulations predict detections in more than 20,000 giant stars. Detections have already been recorded in around 16,000 red giants. Stello et al. (2013) report on the asteroseismic analysis of more than 13,000 red giants (see also Hekker et al. 2011); while another 3000 detections have recently been made from the analysis of targets that were previously unclassified in the KIC (Huber et al. 2014). There are undoubtedly other cohorts of Kepler targets, containing red-giant stars, that have not yet been subjected to asteroseismic analysis (e.g., the so-called add back in stars at the bottom of the Kepler target list). The absolute predictions for the LC data are therefore likely to be fairly robust, and hence the Kepler LC data on red giants should provide testable diagnostics of the underlying binary population, i.e., by giving detections in numbers that are sufficient for drawing statistical inference.

A crucial consideration for drawing any inferences from the real data is of course the likely occurrence rate of false-positives, i.e., the fraction of seismically detected “binaries” we would actually expect to be comprised of spatially coincident—at the i.e., the fraction of seismically detected “binaries” we would statistically infer. By giving detections in numbers that are sufficient for drawing testable diagnostics of the underlying binary population, i.e., by giving detections in numbers that are sufficient for drawing statistical inference.

Figure 5. Orbital period distribution of all binaries (narrow green bars) and detectable seismic binaries (wide yellow bars) in a BiSEPS simulation computed assuming s = 0 (see Section 2.2).

(A color version of this figure is available in the online journal.)

main-sequence) of the core-He-burning phase in higher-mass giants.

Most detectable seismic binaries will have oscillation spectra that overlap considerably in frequency. The observed power in the oscillation spectrum of a solar-type or red-giant star is modulated in frequency by an envelope that typically has an approximately Gaussian shape. With \( v_{\text{max}} \), denoting the frequency at which the oscillations present their strongest observed power, the FWHM of the envelope is a good approximation equal to \( v_{\text{max}}/2 \) (Mosser et al. 2010; Chaplin et al. 2011b).

The bottom panel of Figure 4 plots the difference in the \( v_{\text{max}} \) of the components of asteroseismic binaries (from the TRILEGAL simulations), normalized by the average of the two \( v_{\text{max}} \). When that fractional difference lies within \( \pm 0.5 \), the peak of the oscillation spectrum of each star lies within the FWHM of its companion; the spectra therefore overlap significantly. Only when the normalized difference exceeds unity is the observable power of the two oscillation spectra all but separated in frequency. The bottom panel of Figure 4 shows that cases where the spectra are well separated should be rare.

The distribution of the orbital periods shown by the artificial asteroseismic binaries is plotted in Figure 5. In general it follows the distribution shown by all binaries, but displays a short-period cut-off near 40 days, reflecting the need to accommodate two giant stars.

5. CONCLUSIONS

We have used results from two stellar population simulations of the Kepler field of view to consider potential detection yields from applying a novel asteroseismic method to discover binary systems comprised of solar-type stars and/or red giants. The method relies on the detection of the presence of two solar-like oscillation spectra in the frequency spectrum of a single Kepler light curve. Our predictions suggest that 200 or more binaries may be detectable in this manner using the Kepler data. Most of these binaries should be comprised of two He-core-burning red giants. Owing largely to the limited numbers of targets with the requisite SC Kepler data, we expect only a small number of detected binaries containing solar-type stars.

The method is not biased by, or dependent on, the inclination, period (separation) or velocities of the constituent components.
As such, it may provide the only way to detect some of the binaries that are in the *Kepler* database. The predicted yield of detections is sensitive to the IMRD, which is a robust indicator of the pristine mass distribution at the epoch of star formation (e.g., see Parker & Reggiani 2013). Given the additional constraints, the detection of asteroseismic binaries will also provide targets that are useful for testing stellar models and will add significantly to the list of eclipsing binaries with a solar-like oscillating component (e.g., see Hekker et al. 2010; Gaulme et al. 2013).

Work is now underway to discover asteroseismic binaries in the *Kepler* data archive.

The authors acknowledge useful discussions with J. Ballot, R. García, S. Hekker, D. Stello, and T. White. W.J.C., Y.E., A.M., R.F., and U.K. acknowledge support from the UK Science and Technology Facilities Council (STFC). Funding for the Stellar Astrophysics Centre is provided by The Danish National Research Foundation (grant agreement No. DNRF106). The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement No. 312844 (SPACEINN). We are grateful for support from the International Space Science Institute (ISSI). Finally, we also thank the anonymous referee for comments that helped to improve the Letter.

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The Astrophysical Journal Letters, 784:L3 (6pp), 2014 March 20

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