Kepler as a calibrator for the false positive rate in the PLATO 2.0 transiting exoplanet survey

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The Kepler main mission provided a great deal of data on eclipsing binaries, curated in the Kepler Eclipsing Binary Catalogue (Prsa et al, 2011; Slawson et al, 2011; Kirk et al, 2016). We describe how this data, combined with the population synthesis code BiSEPS (Willems & Kolb, 2002; Farmer, Kolb & Norton, 2013), can calibrate the false positive rates in future transiting exoplanet surveys, in particular PLATO 2.0 (Rauer et al, 2014).

Population Synthesis code: BiSEPS

The Binary Stellar Evolution Population Synthesis code (*BiSEPS*) (Willems & Kolb, 2002; Farmer, Kolb & Norton, 2013) creates a synthetic population of both binary systems and single stars by evolving the stars self-consistently from formation.

These models are then seeded into a model of the Galaxy, which uses the fully evolved models as well as information on extinction. Models can be compared with observations to better understand binary stellar evolution and the observable Galaxy population (Fig 1). A region matching the on-sky field observed by the Kepler main mission was simulated and compared to the current Kepler Input Catalogue on MAST and to Gaia Data Release 1 (DR1).

In Gaia magnitudes (m_G):

- The match to the catalogue on MAST is good at $6 < m_G < 19$.
- The match to Gaia DR1 indicates that more stars are simulated than are included in DR1: this is consistent with the known completeness of Gaia DR1.

Galaxy model:

- Two-disc model (thin and thick), with each disc described by a double exponential.
- Star formation is constant from 13-10 Gyr ago in the thick disc (Z = 0.0033).
- Star formation is constant over the past 10 Gyr in the thin disc (Z = 0.02).
- Kroupa initial mass function.

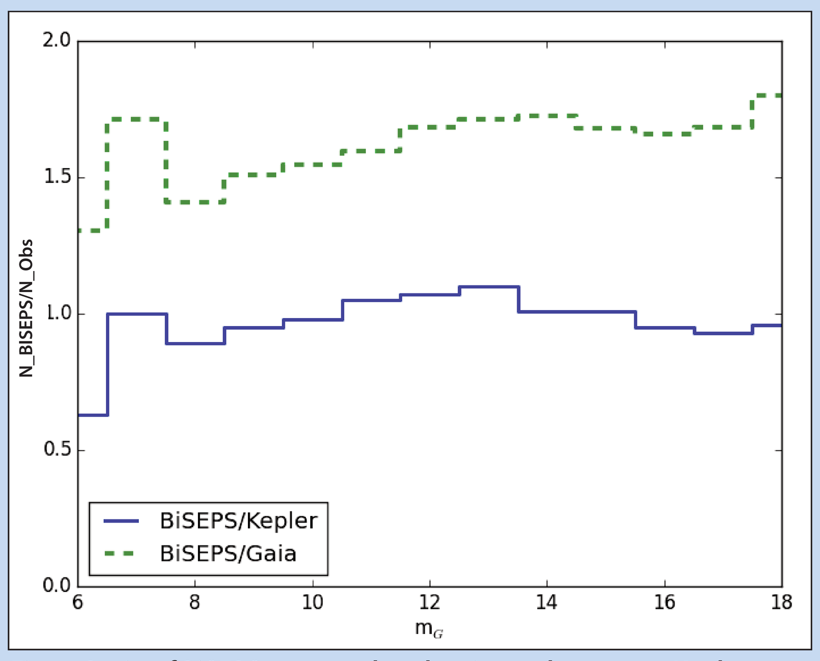


Fig. 1: Ratio of BiSEPS star number density to the current Kepler Input Catalogue on MAST (solid line) and Gaia DR1 (dashed line).

Archives of Kepler data: Kepler Eclipsing Binary Catalogue and NASA Exoplanet Archive

Comparing the NASA Exoplanet Archive (*exoplanetarchive.ipac.caltech.edu*) (NExSci) and the Kepler Eclipsing Binary Catalogue (*keplerebs.villanova.edu*) (KEBC):

- False positives listed on NExSci represent systems examined as a potential planet as a Kepler Object of Interest (KOI). False positives with a significant secondary eclipse are probably eclipsing binaries, and may be blended or unblended.
- Systems listed in the KEBC are unblended confirmed eclipsing binaries: blends, planets and stellar variability may have data available on the website, but carry the designation "False" in the "InCat" (in catalogue) field.

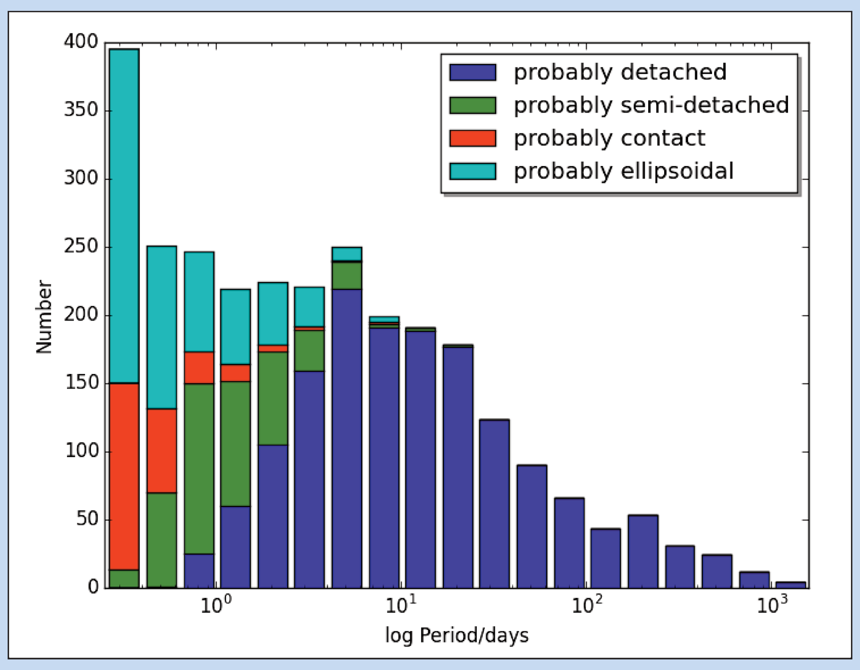


Fig. 2: The likely distribution of unblended eclipsing binaries by eclipsing binary type from the morphology parameter in the Kepler Eclipsing Binary Catalogue. Interpretation of the parameter is from Matijevič et al (2012). Light curves of systems that are probably detached are most likely to appear to be planet-like, especially when blended.

Mass ratio distribution in short period eclipsing binary systems

Systems were selected from the Kepler Eclipsing Binary Catalogue with period .45 days < P < 10 days, an observable secondary eclipse and an estimate of effective temperature T_{eff}. Using BiSEPS and light curves from JKTEBOP (Southworth et al, 2004), the catalogue sample was matched to evolutionary models. Likelihood of formation in a model Galaxy with a Kroupa initial mass function and a flat initial mass ratio distribution was taken into account. Where multiple models provided a match to a system from the catalogue, the relative probability of formation and observation was assessed. We obtain the following mass ratio distribution in this sample of 971 systems.

Fig. 3 shows the distribution of a sample with a flat initial mass ratio: Fig. 4 shows the mass ratio distribution of the sample from the Kepler Eclipsing Binary Catalogue with .45 days < P < 10 days. A detection probability with a flat initial mass ratio does not match observations, while a weighted one does.

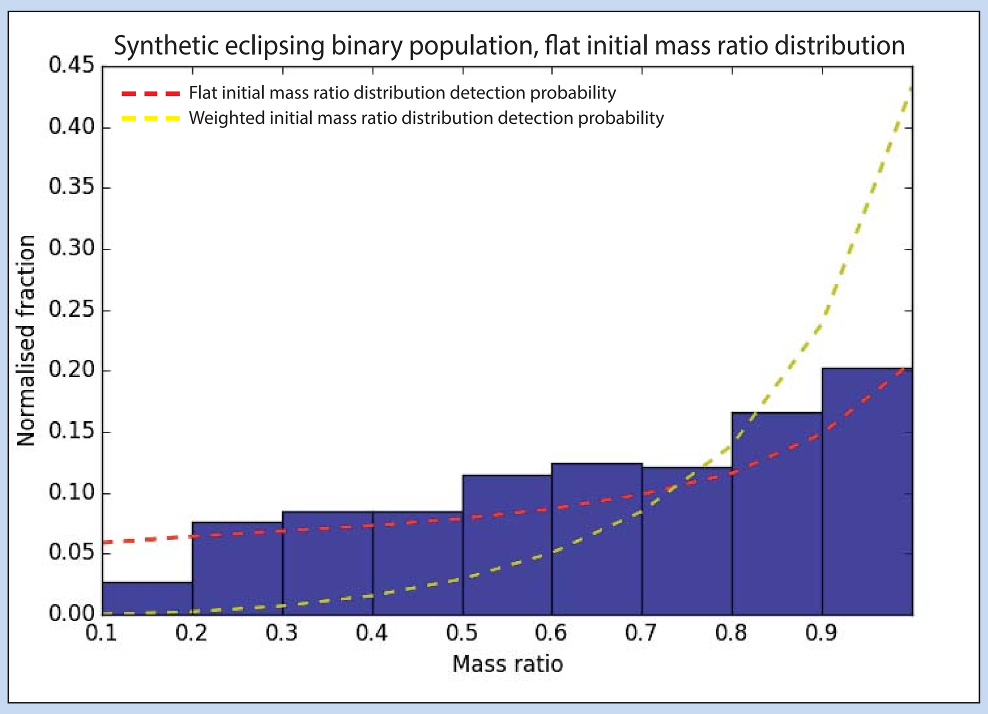


Fig. 3: A synthetic eclipsing binary population with .45 < P < 10 days assuming a flat initial mass ratio distribution, compared to a detection probability calculated with (red) a flat initial mass ratio distribution and (yellow) a weighted initial mass ratio distribution.

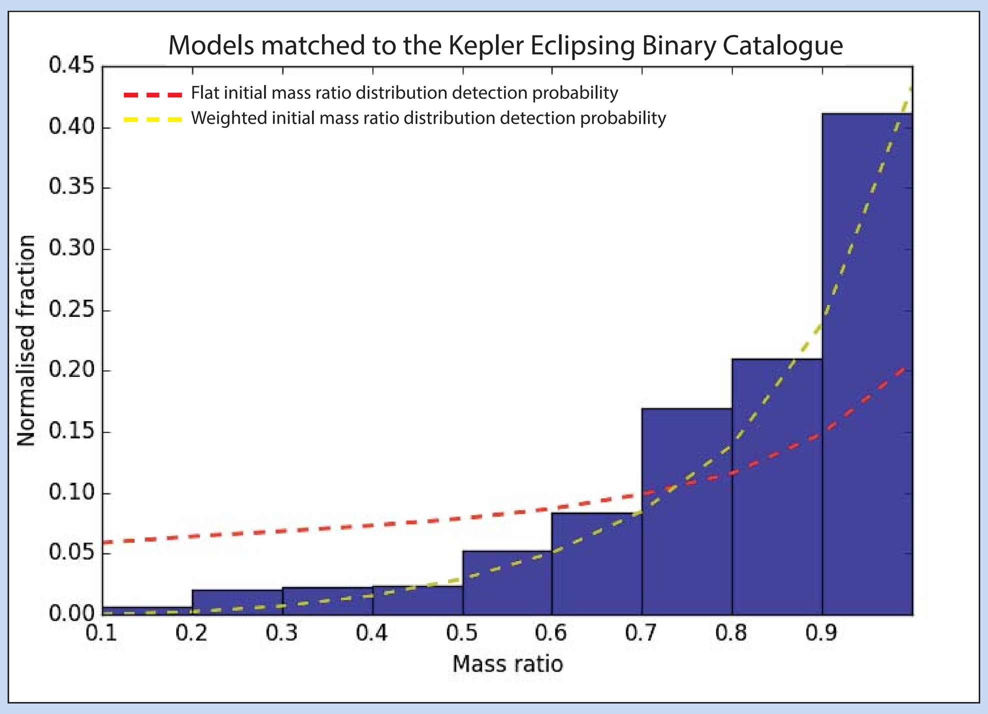


Fig. 4: Models with .45 < P < 10 days matched to the sample from the Kepler Eclipsing Binary Catalogue, compared to the detection probability calculated with (red) a flat initial mass ratio distribution and (yellow) a weighted initial mass ratio distribution.

Initial period distribution of the eclipsing binary population

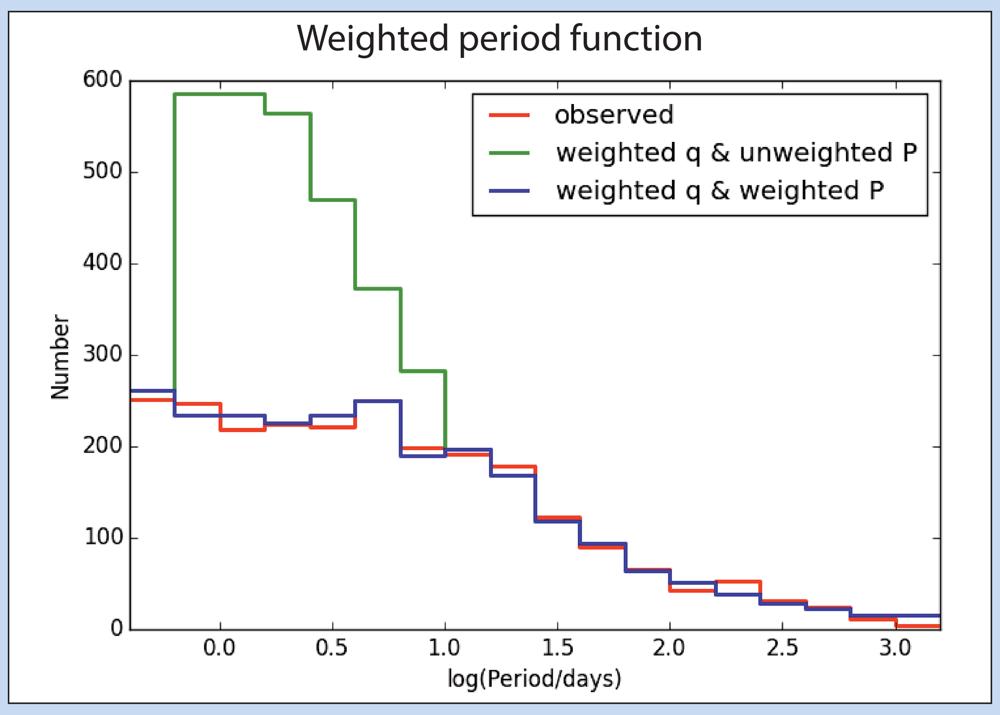


Fig. 5: At P < 10 days, a synthetic eclipsing binary population generated with a flat inital period distribution and a weighted mass ratio for P < 64 days needs to be further weighted to match the observed population in the Kepler Eclipsing Binary Catalogue.

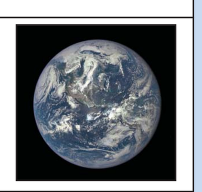
Using a field with a flat initial period distribution, a flat initial mass ratio and matched closely to the composition and on-sky area observed by the Kepler main mission (Farmer et al, 2013), a series of simulations were run to obtain a representative eclipsing binary population.

Comparison between the mean of the synthetic eclipsing binary population and the population in the Kepler Eclipsing Binary catalogue showed:

- A flat initial mass ratio and a flat inital period distribution was the best match for P > 64 days.
- A weighted initial mass ratio (as described in the previous box) and a flat initial period distribution was the best match for 10 days < P < 64 days.
- For P < 10 days a weighted period distribution as well as a weighted initial mass ratio was required to match observations.

An intrinsic exoplanet distribution was generated by applying the exoplanet distribution from NExSci, DR25, to single stars in the BiSEPS field matched to original Kepler Input Catalogue (Farmer, Kolb & Norton, 2013). This could then be applied to the PLATO simulations to obtain an estimate of the planets PLATO will observe, using the signal to noise ratio from the PLATO Instrument Noise Budget, 19 February 2016.

Results

P5 population F5-K7, V < 13	Ratio true planet: EB within 45″	Ratio true planet: EB within 7.5″	Ratio true planet: Unblended EB	Ratio apparent planet: EB within 45″	Ratio apparent planet: EB within 7.5″	Ratio apparent planet Unblended EB	
LLN 0.63-1.0 $R_\oplus$	5.7×10^0 (850/150)	1.4×10^2 (850/6.0)	7.9×10^2 (850/1.1)	5.9×10^0 (890/150)	1.5×10^2 (890/6.0)	8.2×10^2 (890/1.1)	
LLS 0.63-1.0 $R_\oplus$	1.0×10^1 (930/89)	1.5×10^2 (930/6.0)	1.4×10^3 (930/0.63)	1.1×10^1 (970/89)	1.6×10^2 (970/6.0)	1.5×10^3 (970/0.63)	
LLN 1.0-1.6 $R_\oplus$	2.9×10^0 (2700/920)	6.8×10^1 (2700/40)	3.3×10^2 (2700/8.3)	2.8×10^0 (2600/920)	6.5×10^1 (2600/40)	3.1×10^2 (2700/8.3)	
LLS 1.0-1.6 $R_\oplus$	5.5×10^0 (3100/550)	1.3×10^2 (3100/22)	4.4×10^2 (3100/7.0)	5.3×10^0 (2900/550)	1.3×10^2 (2900/22)	4.1×10^2 (2900/7.0)	

Two synthetic on-sky fields were generated covering PLATO 2.0's predicted field of view, one centred on l = 65°, b = 30°, matching the candidate "Long Look North" (LLN) field described in Rauer et al (2014), and the other centred on l = 253°, b = −30°, matching the candidate "Long Look South" (LLS) field described in the same paper.

PLATO 2.0 will have a large plate scale of 15 arcsec/pixel and for each target imagettes will be generated, generally 6 x 6 pixels. A representative minimum and maximum radius for background blends is 7.5″ and 45″ respectively.

Using the intrinsic exoplanet distribution and the calibration of the synthetic eclipsing binary population described in earlier panels, a ratio of planets to eclipsing binaries has been obtained. Both the true radius of the planet, if it is observed unblended, and the apparent radius of the planet, if the transit is diluted by blending with other stellar systems in the same pixel, are considered.

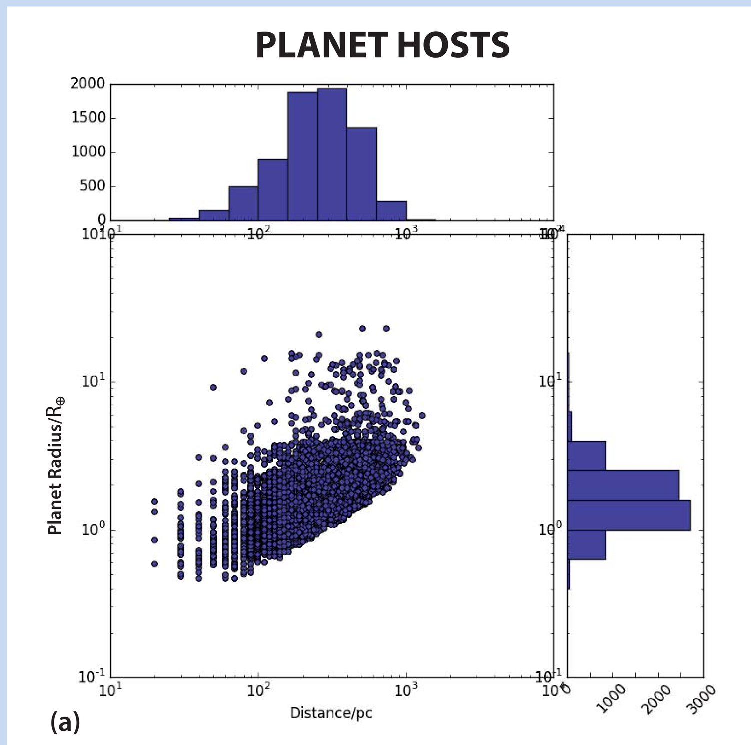
Preliminary results indicate smaller planets significantly outnumber eclipsing binaries of a similar transit depth. The preliminary results for the PLATO 2.0 P5 population, F5-K7, V < 13, are presented here for Earth-like planets (0.63-1.0 and 1.0-1.6 $R_\oplus$).

So why does the ratio for the Long Look South field look higher than the ratio for the Long Look North field?

Analysis of the distance at which planet hosts, unblended eclipsing binaries and blended eclipsing binaries in each field were situated indicates that, for a given apparent planet radius, each sample is limited by distance.

Planet hosts, whether in the Long Look North or Long Look South fields, are close enough that the stellar density is similar in both fields, with the Long Look South returning higher numbers as it looks through the Galactic plane.

Eclipsing binaries, especially blended eclipsing binaries, probe a deeper cone, so variations in stellar density are more apparent, especially when considering blends at > 7.5″: so more eclipsing binaries are observed in Long Look North (l = 65°) than in Long Look South (l = 253°).



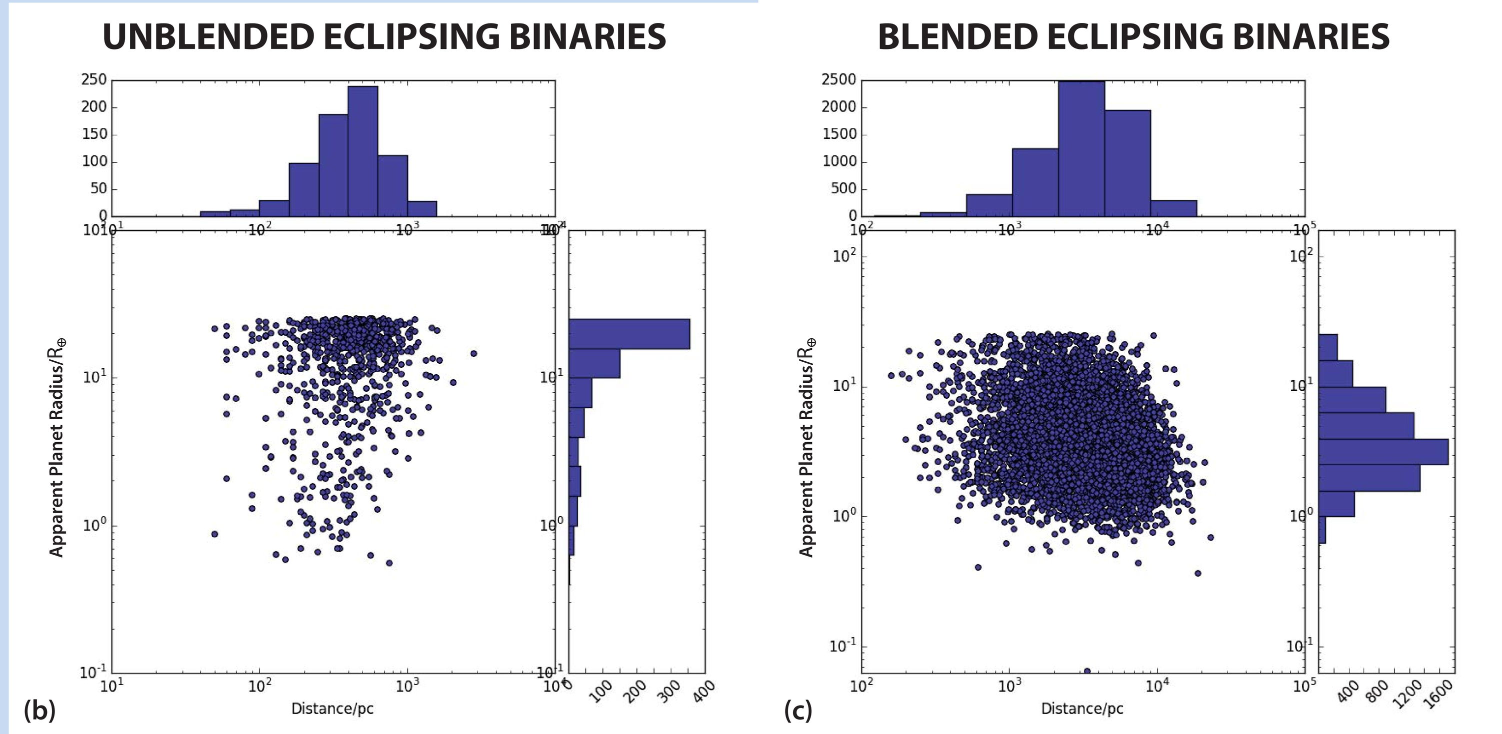


Fig. 6: Distance to (a) planet hosts, (b) unblended eclipsing binaries and (c) blended eclipsing binaries within 22.5″ of the target star, in a P5 population (F5-K7, V < 13) in a synthetic PLATO population. Only eclipsing binaries appearing to be $\log_{10}$ [-0.6, 1.4] $R_\oplus$ are included.

Our research demonstrates that combining synthetic fields generated by the population synthesis code BiSEPS with observations by Kepler enables a deeper understanding of the eclipsing binary population observable in a transiting exoplanet survey. When combined with an intrinsic exoplanet distribution derived from Kepler observations in combination with fields generated by BiSEPS, a reliable prediction of the false positive rate in future transiting exoplanet surveys, such as PLATO 2.0, may be obtained.

References and Acknowledgments

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