Circumbinary planets – the next steps

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Abstract. The Kepler mission opened the door to a small but bonafide sample of circumbinary planets. Some initial trends have been identified and used to challenge our theories of planet and binary formation. However, the Kepler sample is not only small but contains biases. I will present a circumbinary plan for the future. Specifically, I will cover the BEBOP radial velocity survey, the latest TESS transit mission and a new technique for digging out small circumbinary planets in archival Kepler photometry.

Key words: exoplanets – circumbinary planets – transits – radial velocities

1. Introduction

Binary stars are common. Exoplanets are common. It is natural to seek planets in binaries. Planets in binary star systems come in two flavours: circumbinary planets on exterior orbits around tight binaries, and circumstellar planets on interior orbits around one of the two components of a wide binary. Here we will only consider circumbinary planets. The discovery of Kepler-16 (Doyle et al., 2011) really kicked off a search which had been anticipated since before the dawn of exoplanet discoveries (Borucki & Summers, 1984; Schneider & Chevreton, 1991). A dozen or so transiting circumbinary planets have been found by this mission (reviews in Welsh & Orosz, 2018; Martin, 2018), but this paper will look beyond the existing Kepler discoveries.

2. Trends and open questions In circumbinary planets

The dozen circumbinary planets discovered to date exhibit a few interesting trends and pose a few interesting questions.

1. There is a dearth of circumbinary planets orbiting the tightest eclipsing binaries (EBs). Most EBs have a very short period (~ 2–3 days) but the transiting planets are only around > 7 day binaries (Fig. 1a). Muñoz & Lai (2015), Martin et al. (2015a), Hamers et al. (2016) explained
Figure 1: (a) Histogram of Kepler eclipsing binary periods, compared with the periods of binaries known to host circumbinary planets, and the first TESS discovery of TOI-1338/EBLM J0608-59. (b) Left: planet and binary periods; right: planet periapse and binary apoapse. There is a tend for common ratios, which places the planets close to the stability boundary (Holman & Wiegert, 1999). (c) Size and period of Kepler and TESS planet discoveries around both single and multiple stars. Figures reproduced from Kostov et al. (under review) and Martin (2018).
this dearth by invoking a known formation mechanism of tight binaries under
the influence of a misaligned third star and Kozai-Lidov cycles. The appli-
cability of this story has been called into question lately by Moe & Kratter
(2018), who deduce that Kozai-Lidov is only responsibility for the minor-
ity of tight binary formation. More theoretical work is needed. Additionally,
Munoz & Lai (2015), Martin et al. (2015a), Hamers et al. (2016) suggested
that any planets found orbiting around very tight binaries would be likely
small and/or misaligned, both of which have been difficult to find to date.

2. There is an over-abundance of planets orbiting near the dynamical
stability limit. This is likely the result of migratory formation of the plan-
ets, stalling near the edge of an inner disc cavity, which roughly coincides
with the dynamical stability limit (Holman & Wiegert, 1999; Kley et al.,
2019). Whilst this is not the sole result of an observational bias (Fig. 1b),
more detections are needed to determine its statistical significance (Martin
& Triaud, 2014; Li et al., 2016). In particular, finding circumbinary plan-
ets by radial velocities (Martin et al., 2019) or microlensing (Bennett et al.,
2016) would allow for planet detections at longer periods, farther from the
stability limit.

3. All transiting circumbinary planets are larger than $3R_{\oplus}$. This is
contrary to the abundant discoveries of small planets around single stars,
with a comparison shown in Fig. 1c. If it were a real absense, it would be
enlightening, however the lack of small circumbinary planets is a detection
bias; the days-amplitude transit timing variations (TTVs, Armstrong et al.,
2013) inhibit traditional planet detection techniques based on phase-folding
on a fixed period. Only transits of giant planets could be found so far, by
eye. Some algorithms have been proposed to find small circumbinary planets,
using modified versions of Boxed Least Squares (BLS, Ofir, 2008) and the
Quasiperiodic Automated Transit Search (QATS, Windemuth et al., 2019b),
but no candidates have been reported yet.

3. A search for small transiting circumbinary planets in Kepler

The archival Kepler data remains the best source for finding small circumbi-
nary planets, because of its long four-year baseline, high-precision photometry
and well-characterised EB catalog (Prša et al., 2011; Windemuth et al., 2019b).
In collaboration with Dan Fabrycky, a new transit search algorithm is being
specifically designed for shallow transits of small circumbinary planets. It can
successfully recover all known circumbinary planets, and also injected planets
slightly smaller than Earth (Fig 2). Planet detection is assisted by a detrending
algorithm designed specific to EBs, which accounts for the variable length of
circumbinary planet transits as a function of the binary phase. Unique to this
transit detection algorithm is building TTVs directly and exactly into the search. For each set of orbital parameters the algorithm produces a quasi-periodic mask of transit times and durations using a rapid N-body algorithm. This mask is matched to the photometric data similar to the cross correlation technique for high-precision RV fits to spectroscopic data. The N-body-derived mask fully incorporates the three-body geometry and both short and long-term dynamical variations of the planet’s orbit. The search grid has been optimised using principles similar to those of Ofir (2014), but adapted to circumbinary planets.

Roughly two dozen detections are expected if planets have a similar size distribution around one and two stars (preliminary research suggests this is the case for gas giants, Martin & Triaud, 2014; Armstrong et al., 2014). Alternatively, it is possible that small circumbinary planets are rare or non-existent. This would suggest that super-Earths form in situ rather than with significant migration, helping answer a hotly-debated topic (Ogihara et al., 2015); around single stars such a process is possible but around a binary it would be suppressed (Paardekooper et al., 2012).

4. The BEBOP radial velocity survey

Between 2013 and 2018 a blind survey for circumbinary planets was run on the Swiss Euler Telescope. It was given the delightful name BEBOP – “Binaries Escorted By Orbiting Planets.” BEBOP uniquely targeted eclipsing, single-lined spectroscopic binaries. The eclipses add preferential biases in both radial velocity amplitude and transit probability (Martin & Triaud, 2015b; Martin, 2017). The single-lined binaries, composed of F/G primaries and M-dwarf secondaries, avoid the difficult problem of spectral contamination, and the need to deconvolve two moving sets of spectral lines. This is different to the SB2 search of TATOOINE (Konacki et al., 2009).

Over 1000 observations taken over more than 60 nights were compiled in Martin et al. (2019). The survey was sensitive down to $0.5M_{\text{Jup}}$, but our lack of detections showed that circumbinary planets are typically sub-Saturn mass (Fig. 3). BEBOP was sensitive to planetary mass companions at periods of several years, much longer than the Kepler discoveries. BEBOP also demonstrated that there was not a large abundance of giant, misaligned planets, which were proposed by Martin & Triaud (2014); Armstrong et al. (2014) as compatible with the Kepler transit results. BEBOP has since been expanded to large programs on HARPS, SOPHIE and ESPRESSO.

5. The TESS transit mission

TESS presents different challenges and opportunities when compared with Kepler. TESS is observing most of the sky, in both hemispheres, and hence is targeting many more bright stars so ground-based follow-up is significantly eas-
Circumbinary planets – the next steps

Figure 2.: Recovery of an injected 0.875\(R_{\oplus}\) circumbinary planet on Kepler-16 (real planet is over 8\(R_{\oplus}\)) with the new automated algorithm. Injected transits were created using BATMAN (Kreidberg, 2015), with the duration scaled according to the relative planet-star velocity calculated by the REBOUND N-body algorithm (Rein & Liu, 2012).

However, two drawbacks are the smaller telescope size (10.5 cm compared with 95 cm) and shorter observing timespans (30 days for most of the TESS field). Only near the ecliptic poles does the TESS timespan increase to almost a year of continuous viewing, owing to the overlap of multiple sectors. Indeed, the single TESS planet found so far is near the continuous viewing zone: TOI-1338/EBLM J0608-59 (Kostov et al. under review, Fig. 4). The planet has very similar properties to the Kepler population of planets (it is highlighted in Fig 1).

A unique aspect of this discovery, compared with the Kepler discoveries, is that the binary was already known and well characterised as a part of the EBLM (Triaud et al., 2017) and BEBOP (Martin et al., 2019) radial velocity surveys, and those measurements were vital to the planet’s characterisation.

TESS is unlikely to significantly break into new parameter spaces of circumbinary planets, due to the shortened observational timespans and inferior
Figure 3.: BEBOP detection completeness, detected triple star systems (green circles), known transiting circumbinary planets with roughly-characterised masses (upwards blue triangles) and a known circumbinary brown dwarf (downwards blue triangle). Numbers in white boxes indicate 95% confidence abundance bounds. Figure reproduced from Martin et al. (2019).

Figure 4.: Three primary transits of the circumbinary planet TOI-1338/EBLM J0608-59 and the photodynamical fit with its residuals (observed minus calculated). The variable transit duration, owing to a variable relative velocity between the star and planet, is a smoking-gun signature of a circumbinary planet. Figure reproduced from Kostov et al. (under review).
photometric precision to *Kepler*. Most detections will be harder than TOI-1338/EBLM J0608-59. What *TESS* will hopefully provide though is a significant increase in the statistics of circumbinary planets. The *TESS* circumbinary planet working group predicts 140 *TESS* circumbinary planets if we can detect them on a single passing that transits both stars, a “1-2 punch.” This is based on 400,000 eclipsing binaries, a *Kepler*-like circumbinary planet detection rate of 11/2800, a 30/180 chance of the median circumbinary period transiting during a one month window and a 1/2 chance of the planet transiting both stars (Martin, 2017). Based on *Kepler*, ∼70 of these planets are expected to be in the habitable zone.

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