Research Plan at the University of Chicago - David V. Martin

In Martin & Triaud (2014) I identified all of the trends seen so far in circumbinary planets and disentangled them from observational biases. These trends are presented in the table below, with the believed cause of their physical origin or observational bias. *As a Sagan fellow I will hunt for the planets that are presently veiled by detection limitations of the past.*

Trend	Origin	Explanation
Circumbinary planets are all coplanar to the binary orbit (within $\lesssim 4°$).	**Bias**	Coplanar planets produce a series of consecutive transits (i.e. one per orbit), which are relatively easy to detect. Misaligned planets (Fig. 1a) have infrequent transits that are much harder to find.
No circumbinary planets around the tightest eclipsing binaries ($T_{\rm bin} \lesssim 7$ days), despite such binaries being numerous.	**Real**	Very close binaries form via Kozai-Lidov cycles induced by a tertiary star and tidal friction (Mazeh & Shaham, 1979; Fabrycky & Tremaine, 2007). This either prevents circumbinary planets from forming or makes them misaligned and hence harder to detect (Mũnoz & Lai, 2015; Martin et al., 2015; Hamers et al., 2016).
Pile-up of circumbinary planets near the stability limit $P_{\rm p} \sim 5P_{\rm bin}$.	**Real**	Planets migrate inwards in the protoplanetary disc before hitting a truncated edge near the stability limit (Pierens & Nelson, 2013).
Gas giants at least as abundant around binaries as around single stars.	**Real**	Derived in Armstrong et al. (2014) and Martin & Triaud (2014) with different independent methods. A minimum abundance because of insensitivity to misaligned planets.
Circumbinary planets are all Neptuned-sized and larger.	**Bias**	Phase-folding of light curves is needed for small planets but circumbinary TTVs are longer than typical transit durations, inhibiting this for circumbinary planets. All detected systems have individually significant transits.

Scientific motivation

Misaligned circumbinary planets (Fig. 1a): There are many examples of misaligned circumbinary protoplanetary discs, including the polar disc around 99 Herculis (Kennedy et al., 2012), the winking binary KH 15D (Winn et al., 2004) and the recently discovered IRS 43 (Brinch et al., 2016). There is also a theoretical prediction of disc re-alignment over time (Foucart & Lai, 2013). However, even in coplanar discs, misalignment may still be created by planet-planet scattering (Chatterjee et al., 2008; Smullen et al., 2016) or interactions with an outer third star (Mũnoz & Lai, 2015; Martin et al., 2015; Hamers et al., 2016). We also know of planets around single stars that are misaligned (with respect to the stellar spin axis, Triaud et al. 2010). There is also the tantalising possibility that planets actually form more easily around one star than two. In Fig. 1b is the abundance of circumbinary planets as a function of their mutual inclination distribution, which is presently unknown. My research will solve this problem and advance our knowledge of planet formation and evolution in different environments, and the relation to protoplanetary discs.

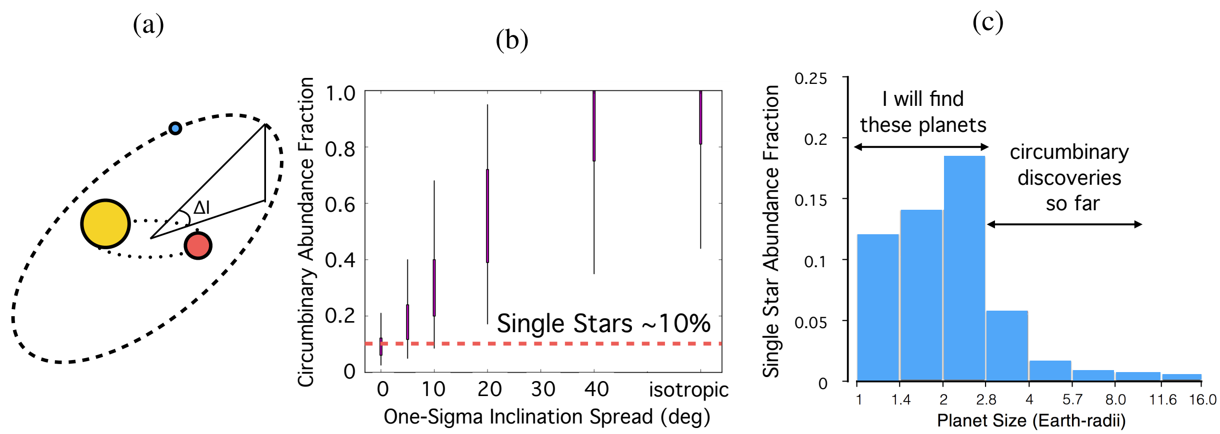

Figure 1: (a) Misaligned circumbinary planet. (b) Circumbinary gas giant abundance vs mutual inclination distribution (Gaussian distribution spread, Armstrong et al. 2014). Purple bars are 50% confidence intervals and thin extended lines are 95%. The horizontal red dashed line is the 10% abundance of gas giants ($> 3R_{\rm Earth}$) around single stars (Petigura et al., 2013). (c) Abundance of planets around single stars vs planet radius (figure adapted from Petigura et al. 2013).

Circumbinary Earths and super-Earths: The abundances of circumbinary and single star gas giants seem similar. There is also evidence that circumbinary planets form far out in the disc where binary perturbations are minimal (Pierens & Nelson, 2013). Together this suggests a similar formation environment. If gas giants form in a similar way around one and two stars, *why not smaller planets?* Around single stars the planet abundance increases sharply for sizes below Neptune (Petigura et al., 2013), shown in Fig. 1c. This coincidentally corresponds to the boundary of the circumbinary detectability to date. Using Petigura et al. (2013) I predict to find at least ~ 50 sub-Neptunes in the *Kepler* data alone, with more to come from *TESS*. On the other hand, the non-existence of such planets would revolutionise our understanding of the differences between gas and rocky planet formation. Finally, with enhanced transit probabilities of circumbinary planets at long periods (Martin & Triaud, 2015; Martin, 2016) I expect to find many habitable-zone planets with temperate atmospheres transiting bright stars, perfect for characterisation with *Hubble* and *JWST*.

The unique methods I will develop and implement

Misaligned circumbinary planets: *Kepler's* sample of almost 3,000 eclipsing binaries has not been exhaustively searched, and using them will be my first step. I will develop an algorithm that detects a series of transits *without* the requirement of strict periodicity and allowing for missing transits, as expected for misaligned planets (Martin & Triaud, 2014). For gas giants each individual transit will be significant and hence no phase folding is required. Clever limits on the TTVs may be placed using the equations I derived in Armstrong & Martin et al. (2013). The detection capabilities will be quantified by the injection and recovery of fake planets. Candidate systems will be analysed in greater depth using the publicly-available photodynamical code by Josh Carter (Carter et al., 2011). The high sensitivity of the circumbinary transit signature on its orbital elements means that tight constraints will be made even with a limited number of transits.

I will then attempt to find *non-transiting* planets around eclipsing binaries by measuring eclipse timing variations induced by the planet. Careful modelling will allow a measurement of ΔI and the detection capabilities will be quantified to constrain abundances. For the brightest stars and heaviest planets spectroscopic followup will better characterise the orbit.

Finally, I will look to non-eclipsing binaries in *Kepler*, increasing the sample size by two orders of magnitude. Martin & Triaud (2014) predicts just as many transits on non-eclipsing binaries, but often only single transits. However, if the binary inclination is say $80 - 85°$, then moderately misaligned planets ($\Delta I \sim 5 - 15°$) can produce a consecutive sequence of at least three transits. Such planets would not appear in any known *Kepler* candidate list because of the large TTVs. I will find them by scanning the entire *Kepler* target list of $\sim 200,000$ stars without any a priori binary knowledge, and apply the same algorithm as previously mentioned. To handle 200,000 light curves the algorithm will have as few as three free parameters (starting time, mean transit separation and TTV amplitude) and will be expedited using Chicago's CPU cluster. Radial velocity follow-up of candidate systems will easily confirm their binary nature.

Circumbinary Earths and super-Earths: Traditional methods do not work; a more bespoke approach is required. The key is a clever phase-folding of photometric data on quasi-periodic transit timings. I will develop analytic work commenced in Armstrong & Martin et al. (2013) and numerical simulations to model TTVs to a precision better than a transit duration. The parameter space is large but there are less than 3,000 eclipsing binaries to search and I will use Chicago's CPU cluster. Most likely only coplanar planets will be detectable such that transits are numerous.

TESS, PLATO and beyond: The essence of my work is to uncover circumbinary planets with less data than past discoveries. This is essential for these future missions with shorter observing timespans. After starting with *Kepler* I will apply my work to *TESS*, for which the stars will be brighter allowing for easier spectroscopic followup (e.g. using Chicago's guaranteed Magellan time). My work will then create a legacy to be applied to the larger *PLATO* mission and beyond.

Circumbinary census: I will uncover circumbinary architectures by combining new *Kepler* and *TESS* planets with not only existing transiting planets, but results from my ongoing *BEBOP* radial velocity survey and *GAIA* astrometry (predictions in Sahlmann, Triaud & Martin 2015).

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