Previous & Current Research - David V. Martin

Over five years I have developed a broad career in exoplanets with three over-arching goals: find them, understand them, and explain them. I have been blessed to work with colleagues across the entire spectrum of exoplanetology. Their wisdom imparted has fostered a well-rounded education and collaborative spirit, whilst also imbuing the confidence and ability to work and publish independently. During my honours degree at Monash University I was supervised by Dr. Rosemary Mardling, a leading expert in celestial mechanics. Then in my PhD at the Université de Genève I received the guidance of Prof. Stephane Udry, a pioneer in exoplanet observations. Rather than conduct a narrow line of research hamstrung by a rigid set of abilities, I have followed the opposite philosophy. Through reading the literature and interacting with colleagues, I have developed a wide range of interests and curiosities. *I then take it as a challenge to cultivate the necessary expertise to answer the questions posed by myself or others.*

To briefly outline the story of my research I first think back to one of the original objectives of my PhD being the study of transit timing variations (TTVs): the effect of exoplanet transits being early or late under the influence of other astrophysical bodies. This technique can better characterise planets and detect non-transiting companions. I saw this as the perfect interplay between orbital dynamics and observational astronomy. I quickly found an application in circumbinary planets - planets orbiting two stars. They had been discovered unambiguously by *Kepler* two years prior (Doyle et al., 2011) and have very large TTVs owing to the binary movement and how it perturbs the planet's orbit. Before even landing in Geneva to commence the PhD, I teamed up with then PhD student Dave Armstrong (Warwick) to calculate circumbinary TTVs in what became Armstrong & Martin et al. (2013). This paper formed the basis of our comprehensive study of the abundance of circumbinary planets in Armstrong et al. (2014), which uncovered the surprising result that gas giants are at least as abundant around two stars as around one.

Circumbinary discoveries continued and I started identifying some trends. For me observations are only as interesting as the deeper physical insight they provide, and so it was important to deconvolve them from omnipresent observational biases. Owing to the complex geometry and orbital dynamics of circumbinary planets, I turned to numerical simulations of the *Kepler* detection capabilities. This required me developing several computer codes and, working with Dr. Amaury Triaud then at MIT, ultimately yielded the publication Martin & Triaud (2014).

I noted that almost all of the circumbinary planets had been found orbiting as close as possible to the binary without being unstable, and my research proved that this was a real effect. This increased the validity of formation models predicting such a "pile-up" (e.g. Pierens & Nelson 2013). Another result of critical importance stemming from Martin & Triaud (2014) was the stark paucity of planets around the tightest binaries (period < 7 days). I suspected it was related to the high-eccentricity formation pathway of such close binaries via Kozai-Lidov cycles (Lidov, 1961; Kozai, 1962) induced by a third star, followed by tidal friction. To confirm these suspicions I connected with Prof. Tsevi Mazeh (Tel Aviv) who first postulated such a formation mechanism (Mazeh & Shaham, 1979), and Prof. Daniel Fabrycky (Chicago), who wrote the seminal paper on the subject (Fabrycky & Tremaine, 2007). Combining numerical simulations and analytic theory we demonstrated that if the closest binaries do indeed form this way then it is compatible with the non-detection of circumbinary planets (Martin et al., 2015). I had taken an observation in exoplanets (in this case a *non*-observation) and used it to further our understanding of stellar multiplicity, highlighting the multi-disciplinary nature of circumbinary planets.

Another conspicuous absence was planets on orbits misaligned to the binary; all of the discovered planets were aligned to within $\sim 4°$. Whilst this is similar to the flat distribution of the solar system, many exoplanets are known that are highly misaligned (relative to the stellar spin axis, Triaud et al. 2010). There are also arguments for the existence of misaligned circumbinary planets, e.g. from planet-planet scattering (Chatterjee et al., 2008; Smullen et al., 2016) or misaligned discs (Kennedy et al., 2012; Brinch et al., 2016). Curiously, the existence of misaligned planets would boost the overall abundance of circumbinary planets beyond that around single stars (Armstrong et al., 2014). Martin & Triaud (2014) we showed that this flat distribution of observed circumbinary planets was an observational bias. Knowing this, I immediately sought means to detect them.

I determined three possible techniques: **First**, a radial velocity survey for circumbinary planets would be sensitive to almost all inclinations. This would require a strong observational knowledge so during my PhD I partook in ten observing campaigns spanning ~ 5 months over three continents. I contributed to both long term radial velocity surveys and follow-up of transit missions such as *WASP*, *Kepler*, *K2*, *KELT* and *NGTS*. With Dr. Triaud and Prof. Udry I constructed the *BEBOP* radial velocity survey for circumbinary planets, for which I am the principal investigator, run on the Swiss Euler Telecsope in La Silla, Chile. By observing single-lined spectroscopic binaries (with M-dwarf secondaries) we avoid issues of spectral contamination that have hampered previous efforts (e.g. Konacki et al. 2009). The results of this ongoing survey will be published in 2017. As a proof of principle test I am also leading a radial velocity follow-up of a known circumbinary planet Kepler-16, with observations continuing throughout 2017. The **second** method was something never considered before: astrometry. Working with Dr. Johannes Sahlmann (ESO) we calculated the detectability of circumbinary planets using the recently-launched *GAIA* mission (Sahlmann, Triaud & Martin, 2015). The advantage of *GAIA* is that one may directly calculate the mutual inclination between the binary and planet orbits. We now eagerly anticipate the upcoming data releases to test our predictions. The **third** means of detecting misaligned circumbinary planets is to follow the predictions of Martin & Triaud (2014) and detect them photometrically using both archival *Kepler* data and upcoming *TESS* data. I showed numerically that misaligned planets are even *more likely* to transit than coplanar ones, but have a more difficult signal to find and interpret, and have hence evaded detection so far. Part of my Sagan fellowship will be to find these planets that I predicted. I already have experience in the analysis of transiting circumbinary planets, working with Prof. Bill Welsh, Prof. Jerry Orosz (San Diego State), and Dr. Armstrong on a *Kepler* candidate that is due to be published next year pending further observations.

It seemed curious and perhaps counter-intuitive to many that misaligned circumbinary planets have *higher* transit probabilities than coplanar ones. As useful as the numerical simulations were at showing this, nothing is as illuminating or elegant as an analytic mathematical treatment. In a series of papers (Martin & Triaud, 2015; Martin, 2016) I derived an analytic transit probability, incorporating the orbital dynamics that govern the varying planetary orbit. It became clear that circumbinary planets had inherent advantages over planets around single stars by being orders of magnitude more likely to transit, even at periods typically considered long for photometric surveys. This elevated circumbinary planets from an exotic niche topic to practical tools in astronomy. Long-period planets transiting bright stars would help better understand the outer reaches of solar systems, and provide candidates for the characterisation of temperate, habitable zone atmospheres. This work also spawned a "spin-off" paper applying the mathematics I have developed to the different topic of exomoons and circumstellar planets in binaries, due to be finished in late 2016.

Whilst working on misaligned circumbinary planets the subject of Kozai-Lidov cycles was constantly raised. They are synonymous with misaligned triple systems, and I had exploited them in understanding the formation of the closest binaries, but would they exist in an isolated circumbinary planetary system? This had been suggested to me by many people, including referees of earlier papers, but they never appeared in my numerical simulations. I therefore took it upon myself to better understand the origin of this effect and analyse it for three arbitrary masses. In Martin & Triaud (2016) I demonstrated clearly how the range and amplitude of Kozai-Lidov cycles vanished as the outer body became small, like a planet. Beyond my initial goals, I unearthed fascinating dynamical effects occurring in the transition regime between triple stars and circumbinary planets, highlighting sharp departures from classical theory. I have since expanded the analysis with Dr. Alexandre Correia (Porto), to include post-Newtonian effects such as General Relativity.

Finally, working on circumbinary planets has fostered a strong interest in the science of binary stars. With Dr. Triaud I am the co-investigator of the long-term *EBLM* radial velocity survey of low-mass eclipsing binaries, originating in the *WASP* transit survey. There is an initial outline in Triaud et al. (2012) and by the end of 2016 we will release over 100 binaries, with another 100 to come the following year. By virtue of using a high-precision planet-finding spectrograph *CORALIE* for a binary survey we have some of the most exquisitely characterised binaries and M-dwarfs know. I am leading the effort to interpret the observations in the context of tidal theory, with preliminary analysis indicating some groundbreaking results are to come. We also have measured spin-orbit angles for many of our binaries using the Rossiter-McLaughlin effect, and the 7-year observational baseline makes us sensitive to long-period companions. Not only can we use such observations to better illuminate the formation history of these binaries, but the *EBLM* survey acts as a comparison sample to the Swiss survey of hot-Jupiters. Finally, the M-dwarfs will fill out a presently sparse region of the stellar mass-radius diagram, critical for theories of stellar structure and also for exoplanet surveys around M-dwarfs such as *MEarth* and *SPECULOOS*.

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