European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME LARGE PROGRAMME PERIOD: **101A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title Category: **C–7**

The BEBOP radial-velocity survey for circumbinary planets: moving forward on planetary formation.

2. Abstract / Total Time Requested

Total Amount of Time: 78 nights VM, 0 hours SM Total Number of Semesters: 4

Planets orbiting both stars of a binary system -circumbinary planets- are challenging our understanding about how planets are assembled and how their orbits subsequently evolve. We aim to assess how similar and how different the orbital and physical properties of circumbinary planets are to the properties of planets orbiting single stars. Our detections will open a new window of investigation into a highly debated topic, and complement observations of circumbinary protoplanetary discs imaged with SPHERE and ALMA.

During 78 nights, our programme will turn HARPS on a unique and carefully selected sample of 40, bright, recently identified, single-line, low-mass, eclipsing binary systems. They have been discovered and characterised in the course of a 10-year long observing campaign. Composed of an F, G, or K + late-M pair, their mass ratios provide optimal conditions for high radial-velocity precision and accuracy, reaching a level where the detection of circumbinary planets with the mass of Neptune is feasible. Based on already discovered systems, we expect to find between 5 and 15 planetary systems orbiting our eclipsing binaries. Discovering them using the radial-velocity method also opens the door to study dynamical effects unique to circumbinary planets, to estimate their multiplicity, and to compute their true occurrence rate, information that has eluded *Kepler*.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	101	HARPS	20n=5x4	any	n	n	THN	v	
B	102	HARPS	20n=5x4	any	n	n	THN	v	
C	103	HARPS	20n=5x4	any	n	n	THN	v	
D	104	HARPS	18n=2x3+3x4	any	n	n	THN	v	

4. Principal Investigator: Amaury Triaud, a.triaud@bham.ac.uk, UK, School of Physics and Astronomy, University of Birmingham

4a. Co-investigators:

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Following CoIs moved to the end of the document ...

5. Description of the proposed programme

A – Scientific Rationale: Despite over two decades of successful exoplanet detections, a number of surprisingly fundamental questions remain unanswered about the formation and orbital evolution of exoplanets. Studying planet formation usually relied on collecting new observables (like the spin–orbit angle; Triaud+ 2010), or on extending the range where planets are found (e.g. over $M_\star$, TRAPPIST-1; Gillon, Triaud+ 2017). Circumbinary planets –planets orbiting both stars of a binary system– offer a totally different route, a unique approach where we will collect exactly the same observables as for planets orbiting single stars, but for planets that experienced a different assembly, and an altered migratory history. Every difference, and each similarity in the planets' occurence rate, in the distribution of orbital elements (period, eccentricity, inclination), in the physical properties (mass, host's metallicity, multiplicity) will become a novel test for theory.

The study of circumbinary planets is in its infancy. The first unambiguous detection of a circumbinary gas-giant is recent: Kepler-16b (Doyle+ 2011). Arguably, this discovery produced the most surprising result coming out of the *Kepler* mission. *Kepler* identified 11 circumbinary planets (5 gas-giants), in 9 systems. This informed us that circumbinary planets occur at least as frequently as planets orbiting single stars (Martin & Triaud, 2014, Armstrong+ 2014). One serendipitous detection was made using radial-velocity (HD 202206c; Correia+ 2005), which was only confirmed recently (Benedict+ 2017). Circumbinary gas-giants, like around single stars, range from 0.1 to >10 $\mathrm{M_{Jup}}$. *Kepler* has given us a glimpse of these fascinating systems, raising many questions that we now wish to investigate. So much remains to be known about these exotic worlds.

Circumbinary planets offer a new perspective on planet formation.
Two stars at the centre of a circumbinary disc disturb it, and prevent planetesimal accretion within 50 orbital separations of the binary (Meschiari 2012, Paardekooper+ 2012, Rafikov 2013). For the vast majority of binaries, that separation is beyond Jupiter's orbit. This hampered accretion process implies: 1) a reduced occurrence rate compared to single host stars (contradicting observations), and 2) an efficient migratory process since all *Kepler* circumbinary planets were found well within Jupiter's separation (Fig. 1a). Improving the discovery and characterisation of multiple circumbinary planets will offer tighter empirical evidence that theory will have to match. Furthermore, circumbinaries can shed light on the processes that are relevant for planet formation and evolution in single star systems: A current debate rages on whether Neptune and sub-Neptune mass planets form within the snow line, or further away from it (Lee & Chiang 2016, Izidoro+ 2017). Circumbinary detections suggest the latter, that migration is a viable, and relevant process. Arguments on the assembly and disc-driven migration of gas-giants are similarly affected (e.g. Batygin+ 2016). *Kepler*'s unexpected detections also hint to an over-density of planets near six times the binary period (Martin & Triaud 2014), around where disc-driven migration is expected to cease (Kley & Haghighipour 2014). The amplitude of that pile-up carries information on the migration rate, and the forces applied on the planets by the disc.

N-body simulations confirm that planet-planet interactions, notably planet-planet scattering, occur similarly in circumbinary environments, as around single stars, meaning similar distributions in eccentricity, and mutual inclination (ΔI; Smullen+ 2016). A distribution of $\Delta I = 0 \pm 30^\circ$ is a predicted result (Chatterjee+ 2008).

Single, metal-rich stars, host gas-giants more frequently than others (Udry & Santos 2007). This result is widely interpreted as a confirmation that core accretion is the main process behind gas-giant formation (Mordasini+ 2012). We will check whether metal-rich binaries too are more likely to host gas-giants, despite a context where core-accretion is thought to be stiffled. This is another example where circumbinaries would help us test what we think we know on planet formation. *To complete these goals we need to start increasing our available sample.*

During BEBOP (Binaries Escorted By Orbiting Planets), we will monitor 40 nearby single-line eclipsing binaries with HARPS, seeking multiple new circumbinary planets. Our detections will represent a natural comparison sample. Every compared observable will create a novel test for theory, enquiring about planet formation where only one variable has been affected: the presence of two stars instead of just one at the centre of the system.

Kepler's shortfalls, and the dramatic effect of mutual inclination.
Kepler's transit method is heavily geometrically biased towards the shortest orbital periods. In addition, *Kepler* is severely affected by a planet's inclination to its binary's orbital plane (ΔI). Any $\Delta I > 0$ induces a precession of the planetary orbit. The planet misses transits, sometimes skipping them for decades. Therefore, *Kepler*'s 4-year tally is incomplete, and we could only measure a lower bound on the circumbinary planet occurrence rate. Assuming that all circumbinary planets are strictly coplanar (the most conservative assumption possible), we find that >10% of close binaries (>13% when removing perturbing triples) are accompanied by gas-giants (Martin & Triaud 2014, Armstrong+ 2014), a rate that matches gas-giants orbiting single stars (Mayor+ 2011). Should circumbinaries instead follow a normal distribution as tight as $\Delta I = 0 \pm 5^\circ$, current detections imply an actual occurrence rate three times higher than the lower bound. This provides a tantalising and astonishing prospect, that planet formation, or planet migration, is more efficient in binary systems than around single stars.

Radial-velocities to the rescue.
Our HARPS survey does not suffer the biases *Kepler* did. Our detections will measure a true occurrence rate, and obtain a better assessment of the efficiency of planet formation in circumbinary environments. Furthermore, combining our rate with *Kepler*'s rate will provide an indirect measure of ΔI. RVs can measure masses

more robustly. RVs are more sensitive to multiple planets, and not as biased in terms of orbital separation and inclination. Furthermore, RVs can match *Kepler*'s yield spending only 2% of the observing time (78 nights vs 4 years), at a tiny fraction of the cost. Contrary to *Kepler*, we can better select, and better control our sample (e.g. stars that are 3.5 mag brighter), and will be able to study any detections for years to come. Whereas surveys such as those conducted by *Gaia* and SPHERE focus far from the hosts (Thalmann+ 2014, Bonavita+ 2016), we look at tighter orbits. Our observations will also complement an increasing number of ALMA results on circumbinary discs, and of the dust coagulation that happens in them (Boehler+ 2017).

Feasibility. We conducted a pilot programme with HARPS, and demonstrate that we reach the correct precision to detect, and recover gas-giants on orbits of a few months orbiting our binary stars (Fig 1a & 2). Our binary sample is special. It consists only of carefully selected **eclipsing single-line binaries**. Because the secondary star is not detected, we can accurately recover a planet as light as Neptune (Fig. 2c).

A sample constructed to maximise detection and characterisation.
Our 40 systems were meticulously selected from a sample counting over 300, all of them single-line eclipsing binaries, that we have characterised for 10 years using the CORALIE spectrograph. By requiring they are **eclipsing binaries**, we nearly guarantee that one day the planet will precess into a transit (see legacy). Furthermore, our binaries constitute a new and unique ensemble of F, G or K dwarfs eclipsed by a very low-mass M dwarf ($< 0.2 M_\odot$), **single-line binaries**. Our M dwarfs have radii and temperatures similar to the gas-giants found by WASP (Triaud+ 2017). This removes any potential contamination to the RV signal: according to the luminosity law, our low-mass secondaries emit as much light as hot Jupiters re-emit (Triaud 2014). **Searching for circumbinary planets on single-line binaries is exactly like searching for a multiplanetary system orbiting a single star**, something routinely achieved by HARPS (e.g. Díaz+ 2016). Our test observations collected with HARPS (099.C-0138, Fig 1a & 2), and HD 202206c (Correia+ 2005; Benedict+2017) confirm **there is no impact from the binary**. Additional important properties are:

– Our systems are in average *3.5 magnitudes brighter* than *Kepler*'s confirmed circumbinary systems;
– Our sample has parameters compatible to where *Kepler* detected most of its planets (Fig. 3);
– All our binaries have period $P_{\rm bin} > 6$ days where we are more likely to find planets (Martin+ 2015);
– We cleaned the sample of nearby perturbing tertiary stars (35% of our original sample);
– We removed systems showing signs of stellar activity (which otherwise could hide a planet);

Expected yield of our programme.
Circumbinary planets form a new, mostly unexplored frontier. We note that every time a new region of parameter space has been explored, surprising results emerged. Hot Jupiters were not anticipated, yet they exist. Super-Earths were predicted to be entirely absent; they are the most abundant planet population we know. Circumbinary planets were unexpected to form, but are at least as frequent as around single stars.

We will survey 40 eclipsing binary systems with the HARPS spectrograph. Our programme is designed to achieve the best sensitivity on each system. We can detect planets with masses as low as 0.1 $M_{\rm Jup}$, at an orbital period six times longer than its binary (where there is a planet over-density, Martin & Triaud 2014). Our sensitivity covers a mass range comprising all *Kepler* circumbinary gas-giants, and extends over a wider area of parameter space, reaching higher planetary masses and much longer orbital periods (> 1 $M_{\rm Jup}$ for P>10 yrs).

The most pessimistic yield scenario is to assume strict coplanarity, and invoke a planet occurrence rate of >13% of systems. In this case, **we forecast at least five planetary systems** (Fig. 1b). However none of the *Kepler* detection is exactly coplanar, meaning that the actual occurrence rate can only be larger than 13%. Furthermore, there is mounting evidence for frequent non-zero ΔI: Kepler-413b, $\Delta I = 4.1 \pm 0.1^\circ$ (Kostov+ 2014); HD 202206c, $\Delta I = 6 \pm 2^\circ$ (Benedict+2017), Welsh+ (Aspen conference 2017) described two systems with $\Delta I > 10^\circ$. Earth's orbit itself is 7° inclined to the Sun's equator.

If, as seems more likely, circumbinary planets occupy orbital planes following a distribution of $\Delta I = 0 \pm 5^\circ$, **we expect ~ 15 systems** (Fig. 1b). We assumed one planet per system but RVs are much more sensitive to additional planetary companions than *Kepler* was. Our final yield is likely to surpass our assessments.

Incorporating the OPC's feedback. We proposed this programme a few periods ago. In addition to positive comments, the OPC questioned whether the selection of SB1s introduced a bias for any comparison between circumbinary planets and planets orbiting single stars. We think SB1s represent the least biased sample in that respect, since the mass contribution of the secondary to the overall mass of system is the closest to that of a single star. The OPC's second and third points were more influential. Our previous proposition intended to survey more binaries, in a shallower way. The OPC correctly remarked that our search region was not sensitive enough to cover the parameters of all of *Kepler*'s circumbinary gas-giants. Consequently, we proposed, and were approved a pilot programme, on two binary systems, to demonstrate that binarity is not detrimental to reaching lower masses (which remained untested). Our results are conclusive (Fig. 1a & 2). Our two targets were on either end of the range of our sample. Collecting 30 HARPS measurements, our sensitivity achieves 2 m/s (photon noise) sufficient to cover most of the gas-giant range. In addition, the recent discovery of Kepler-1647 (Kostov+ 2016), and the new astrometric mass of HD 202206c (Benedict+2017) confirm as we had suspected, that circumbinary planets with masses above Jupiter's, do in fact exist. Indeed, that circumbinary planets also

5. Description of the proposed programme (continued)

occupy a wider range of ΔI than previously thought. We believe that we now propose an improved observing campaign focusing, as advised by the OPC, on a smaller sample, but with a much improved and tested sensitivity.

A lasting legacy: more planets, the measure of ΔI, a transit search & atmospheric studies
Our BEBOP programme is a first significant step. We intend to eventually cover the rest of our large binary sample, to extend the survey to the North, but also to learn how to deal with double-line binaries, and open more systems for planet discoveries. Careful future RV observations, and a modelling of Newtonian effects will allow us to measure ΔI (like done in Correia+ 2010) for each system, thanks to which we can predict transits. The BEBOP detections will have periods of weeks to months. These are called *warm Jupiters*, planets cool enough that their clouds have likely sank below observable levels (Marley+ 2012), while hot enough that water remains in the gas phase. This property makes them prized targets to measure the chemical content of their atmospheres, from which additional clues about their formation and migration can be obtained (e.g. Öberg+ 2011). Warm Jupiters orbiting single stars have transit probabilities between 2 and 0.5%. Thanks to orbital precession and the eclipsing configuration of the binary, $\sim 95\%$ of BEBOP's detections will eventually transit (Martin & Triaud 2015). Only three gas-giants with periods > 30 days transit stars brighter than $J = 12$; *TESS* will find one more only (Ricker+ 2014). While it will take decades for all our discoveries to transit, waiting they precess into a correct configuration, we expect that progressively nearly all 15 will do so (Fig. 4c).

Concluding words.
Circumbinary planets are poorly studied because they have traditionally been harder to observe, which we resolved by concentrating on single-line binaries. This is one of few topics where bold advances can be made. In 78 nights, HARPS will match, likely surpass *Kepler*'s yield (a 4-year survey) and give us characterisable planets. Studying circumbinary planets and their distribution has direct consequences in our understanding of stellar and planetary formation. Having realised that they also offer unique properties leading to new opportunities for atmospheric characterisation, we successfully confronted the difficulty of finding planets around binaries and constructed an original programme, able to expand our perception of exoplanets in new ways.

B – Immediate Objective: We will acquire 30 HARPS spectra, over four semesters, on each system. They will be fitted together with the 15-30 CORALIE measurements that have already been collected and that span up to 10 years. This is sufficient to adjust for the two Doppler reflex motions produced by the planet and the binary (see Fig. 2): a total of 12 free parameters. The data reduction is described in box 6.

Expected scientific output: Our HARPS and CORALIE spectra will provide the following:
– From a restrictive >13% occurrence rate, we expect to discover at least five new circumbinary gas-giants. We expect 15 if the standard deviation in ΔI is as large as $5°$. This surpasses the *Kepler* yield, but finding them on bright, nearby, eclipsing systems, which will render possible a host of additional characterisation observations.
– The exact number will produce a true occurrence rate, to be compared to *Kepler*'s lower bound, and infer a general ΔI distribution. Our discoveries will test the presence of a pile-up at the stability limit (Martin & Triaud 2014) and if circumbinary planets can exist on misaligned orbital planes.
– Measurements span two years. They will reveal the presence of multiple planets in each system. We can compare those rates to those of single star systems to provide clues about planet formation processes.
– Spectra give the fundamental parameters of the primary: its $T_{\rm eff}$, metallicity, $v \sin i_1$, $\log g_1$ and spectral type.
– We will check whether gas-giants occur more prominently on metal-rich binaries, to test trends that have been detected for gas-giants orbiting single stars (e.g. Udry & Santos 2007), and appear to support core-accretion.

Because our binary systems eclipse, our data will also yield:
– The eclipses of our systems resemble those of hot Jupiters transiting single stars, since our secondaries have similar sizes (Fig. 4a). A combined fit of RVs and *TESS* photometry provides the primary's mean stellar density, to be compared to the surface gravity $\log g_1$. We also obtain directly $\log g_2$ (Southworth+ 2004).
– Using derived stellar parameters and iterating in stellar evolution tracks, we can get accurate masses and radii of the primaries, the secondaries's true masses, their radii and ages (Maxted+ 2015).
– With the mass of the inner binary known, we will compute the minimum mass of our planets.
– If the binary and planet orbital planes are mutually inclined, the planetary plane will precess on the sky, leading to a modulation in the planet's minimum mass on timescales determined by the system's parameters such as the binary mass ratio, period and eccentricity (Doolin & Blundell 2011), and measuring ΔI.
– We will predict transits and seek to confirm those events. That will refine the orbital parameters and allow to better predict future events. We will then start studying the atmospheres of our planets.

C – Telescope Justification: There are no accessible, suitable, stable, high-resolution, high-precision spectrograph, other than HARPS in the Southern Hemisphere, where our targets are located. We have already performed extensive reconnaissance observations to prepare for this programme using the CORALIE spectrograph, collecting data for ~ 50 nights over ten years. CORALIE lacks precision and often struggles to detect circumbinary gas-giants with masses 2 to 5 times Jupiter's (Fig. 2c).

D – Observing Mode Justification (visitor or service): Visitor mode, the only available for La Silla.

5. Attachments (Figures)

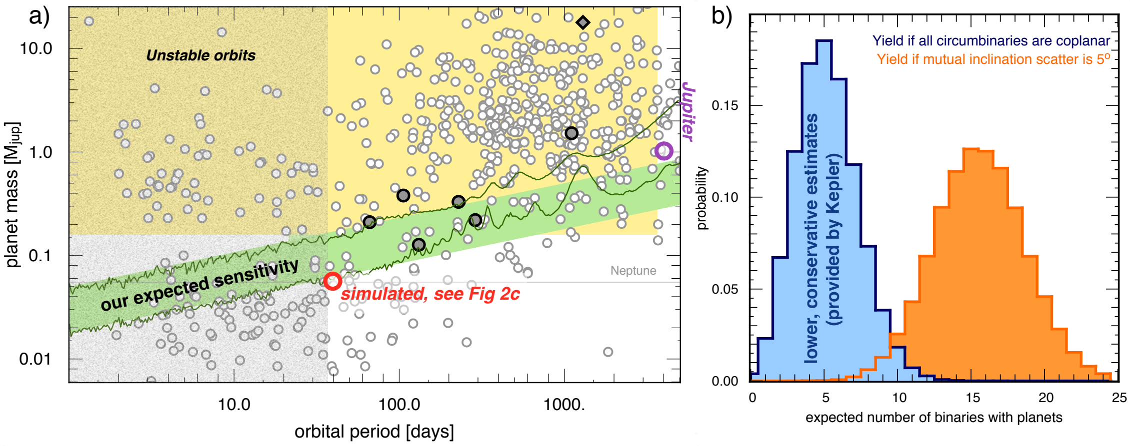

Fig. 1: **a)** Mass/period diagram of radial-velocity detected planets orbiting single stars (grey). All circumbinary planets with measured masses are represented (*Kepler*: black circles; HD 202206c (Benedict+ 2017): black diamond). *Kepler* is mostly insensitive to planets with periods > 1yr. Planets considered as gas-giants are in the yellow box (Mayor+ 2011). The blurred area approximately depicts unstable orbits (Fig 4a). **Our survey focuses where most systems have been discovered orbiting single stars** while covering all known circumbinary gas-giants. This ensures a most impactful comparison between single-star gas-giants and circumbinary gas-giants. The planet density rises at periods > 1yr is interpreted as a sign of disc migration. We will show whether this is the same for circumbinary planets. The green lines represent the 5σ (blind) detection sensitivity reached over two-three months by the two binaries we monitored as part of our HARPS pilot programme (and combined with CORALIE). The green area highlights the theoretical range of sensitivity of our survey (range mostly caused by various binary masses). The observed sensitivities deviate from the expectation only because the HARPS data covers 2-3 months. Longer observing timespans will bring the two together. Normally our HARPS sensitivity ought to plummet beyond the 2-year survey. This is where we really benefit from our CORALIE effort. HARPS can detect slopes and curvature, to which the CORALIE data contributes its long timespan, bringing down the sensitivity to a Jupiter analog. No other sample could possibly do that. (CORALIE on its own could only blindly recover planets in the 2-5 Mjup on short orbits.)

b) Expected yields of our survey. In blue we assume that all circumbinary planets are coplanar, which we know is not correct (e.g. Kepler-413b = 4°: Kostov+ 2014; HD 202206c = 6°: Benedict+ 2017). This represents the most conservative estimate. Instead, we could assume (in orange) that planets follow a ΔI distribution with a standard deviation of 5° (planet-planet interactions cause 30°). **The yield of our survey will produce the first true and unbiased occurence rate for circumbinary gas-giants**. Our yield compared to *Kepler*'s, will provide an indirect measure of the ΔI distribution. Even in the most conservative setting (strict coplanarity), the survey is 9x more likely to detect three or more systems with planets, than two or less.

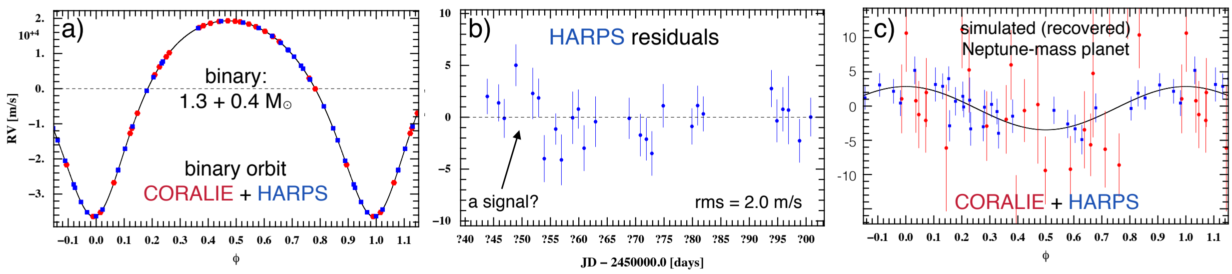

Fig. 2: **Results from our pilot programme: a)** binary orbit of J0310-31, containing 26 CORALIE measurements (over 6 years), and 27 HARPS measurements (over two months), obtained during our pilot programme. **b)** Residuals of the HARPS measurements after removing the binary, achieving a ground-breaking 2m/s rms scatter (1.04x photon noise). **c)** Simulated Neptune-mass planet (see Fig.1a) inserted on the data, and blindly, successfully recovered despite non ideal observing conditions (data covers only 1.5x the simulated orbital period).

5. Attachments (Figures)

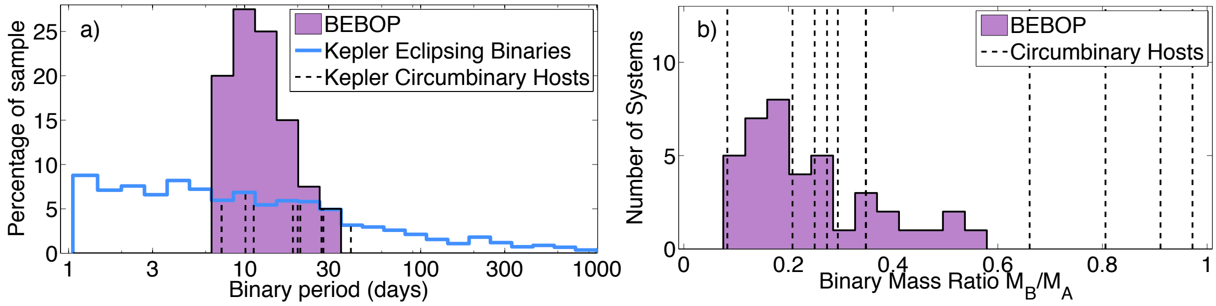

Fig. 3: Our targets are all single line binaries composed of a solar-like primary (with spectral types ranging from mid-K to early-F and masses ~ 0.7 to ~ 1.4 $M_\odot$), and of a late M type secondary (masses from ~ 0.08 to ~ 0.4 $M_\odot$). Most have eccentricities < 0.2. **This is the largest known sample of eclipsing SB1s.**

On all panels, the dashed lines show that our BEBOP sample corresponds to most current known detections.

a) Histogram of the *Kepler* eclipsing binaries (blue), and of our binary sample (purple). No eclipsing binary with period < 6 days has detected planets in *Kepler*, which we adopt as well. The BEBOP sample covers the range of *Kepler* detections. The lack of planets on short-period binaries is interpreted as being caused by triple stars (e.g. Martin+ 2015). Thanks to our reconnaissance, we could remove triples from our sample.

b) Distribution in mass ratios. Low mass ratios, like our sample, appear marginally more likely to host planets despite being less represented in Nature. Our BEBOP sample covers most of the range of current detections, including HD 202206 (left-most dashed line).

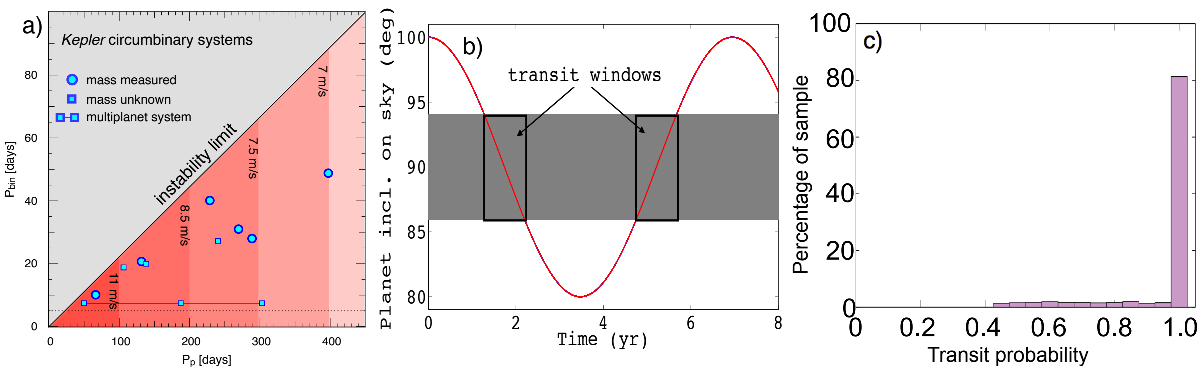

Fig. 4: **a)** Binary period vs the circumbinary planet periods (circles represent systems with masses, squares those lacking a mass). Doppler signals created by 0.2 M_{Jup} planets are noted (for a 1+0.2 $M_\odot$ system) and well within range of HARPS. HARPS's precision is typically 20 times better than CORALIE's (9x the flux, instrument much more stable, double the resolution). The grey area shows where no orbital period is stable (Holman & Wiegert 1999). This shortens the available parameter space and means we can schedule our observations more optimally to explore what is physically plausible. From geometrical considerations, the apparent pile-up of planets along the stability limit is probably not an observing bias, but a genuine feature, likely originating from formation or migratory processes (Martin & Triaud 2014); our observing program will confirm this.

b) Variation in the orbital inclination of a 52 day planet orbiting a 10 day binary, with $\Delta I = 10°$. Where the red curve crosses the grey area shows which inclinations are likely to produce transits. These special moments happen for $\sim 10\%$ of the precession period, which lasts seven years. The majority of our systems are most likely to have smaller ΔI, but this shows how even inclined planets can still transit if they are circumbinary.

c) We estimated the probability of transit given a planet exists orbiting our binaries. For a distribution in mutual inclination ΔI with a standard deviation $\sigma = 5°$, 80% of systems obtain a 100% probability of transit. Integrating this histogram we reach that 95% of our circumbinary planets will enter a transiting configuration during the course of their circulation (for $\sigma = 1°$, the transit probability becomes 75%). A one year period planet orbiting a single star instead has a tiny 0.4% probability of transit. We exceed this by two orders of magnitude. After radial-velocity detection, we will wait for precession, and seek transits of our planets.

6. Experience of applicants with instruments, data quality assessment, data reduction and data product delivery

Members of the team include high-profile researchers in the exoplanet field. Experienced observers with high-resolution spectrographs will carry-out the HARPS observations. Our team has an extensive expertise on the measurements of high precision radial velocities. Some in particular have built the HARPS spectrograph, as well as developed and implemented the various improvements of the online HARPS DRS pipeline. The online HARPS DRS pipeline delivers calibrated high-resolution spectra and high-precision radial velocities. In the past years, the team has developed the infrastructure to handle large amount of spectroscopic data coming from CORALIE, HARPS, HARPS-North, FLAMES, UVES and SOPHIE.
The entire data will be made public after our survey has ended. The radial velocity products, from the most up-to-date data reduction will be made available to all through the DACE interface (dace.unige.ch).
Some Co-Is are stellar spectroscopy specialists. Others are in charge of conducting complementary observations, in particular with the photometry. Several members have a long standing experience in conducting large surveys, photometric and spectroscopic (HARPS GTO and WASP+CORALIE). Dynamicists are also part of the project, to extract the most out of the likely binary-planet interactions.
The DRS automatically provides the reduced and correlated spectra from which radial velocities are computed. Those files are systematically stored on ESO's database. Radial velocity products will be made available through the ESO archive, and through the DACE interface, at the end of our proprietary period, or as soon as we publish a detection.
Similarly, codes to adjust circumbinary orbits are planned to be accessible to the public, through DACE. DACE is a platform of the National Center of Competence in Research (NCCR) PlanetS financed by the Swiss National Science Foundation. It is a data repository, but also an online fitting tool. It aims to be open to anyone who wishes.
The dynamicists in our team have codes that are ready to fit circumbinary planets, and exploit their Newtonian effects to better quantify the systems' physical and orbital parameters.

7. Data product delivery plan and the team's resources, e.g., computing facilities, research assistants, etc.

The official pipeline's reduction reaches a precision below 1 m/s; our photon noise limitation means we will stay above this. In addition, we have our own archive and DRS pipeline on dedicated computers. We can thus continuously experiment new, potentially more efficient, ways of extracting the Doppler information from the spectra (F. Pepe).
The complex orbital solutions to be found for circumbinary systems require global blind solution finders (genetic algorithm, etc), n-body integrations of the systems, and stability checks. D. Ségransan is developing and maintaining an integrated tool including all these features, as well as signal treatment tools and visualisation capabilities which will become part of DACE. D. Martin, A. Correia and R. Mardling are pursuing new avenues with regards to improving and implementing dynamical aspects into the fitting procedures.
C. Hellier, P. Maxted, D. Pollacco, and A. Collier-Cameron are part the WASP team, that supplied the early photometric signal that led to CORALIE (A. Triaud) observing and confirming our eclipsing binary sample. P. Maxted is an expert at dealing with CORALIE and HARPS spectra to extract essential stellar parameters and detailed abundances. As part of WASP A. Triaud, A. Collier-Cameron developed codes ables to combine all photometric and spectroscopic observations able to extract the most out of our data and produce the best description possible of our systems. A. Triaud, D. Martin, A. Santerne are working on circumbinary planets, studying them in the context of *Kepler*, whose insights led to this proposal.
Several co-Is are members of the consortium that is building the *CHEOPS* satellite, under mandate from ESA, which will search for transits too. M. Gillon will help seeking transits using TRAPPIST.
A. Triaud (PI) has recently been appointed at the University of Birmingham in order to study and characterise circumbinary planets. He is creating a small group and will bring new students to the project.

The most optimally determined radial-velocity data will be available publicly on DACE a year after the end of the survey, or at publication, whichever comes first.

8. Special remarks:

To optimise our observations we have asked for five blocks of 4 nights per semester. To help with scheduling, minimise the number of observers, and since we are best served with observations taken randomly during the entire visibility of our targets, we have approached other Large Programs and agreed on an exchange of telescope time, as it was successfully experienced in the past.

We applied for only four semesters. The same amount of nights spread over six semesters would be preferable, but this was not offered in this call.

9. Justification of requested observing time and observing conditions

Lunar Phase Justification: We have no lunar phase requirements. Our selected mode will place a fibre on the sky to correct for lunar-light contamination.

Time Justification: (including seeing overhead) From our hundreds of binaries, we removed all those with signs of a perturbing tertiary, and all those presenting strong stellar activity.
The HARPS ETC provided signal to noise ratios (for z = 1.2 and seeing = 1.2"). They were converted into radial-velocity precision, based on our extensive knowledge of HARPS, and calibrated on our CORALIE observations. The targets we will observe rotate sufficiently that their spectral lines are broadened compared to the instrumental resolution. This impacts radial velocity precision, and we took this into account. The line width was measured on data from our WASP+CORALIE preparatory search for low-mass eclipsing binaries.
We need 30 radial velocity measurements to search for a planet's period and reach the 5σ detection sensitivity in Fig. 1a. We base this assessment on our pilot programme. This is enough points to fit for the binary, for the planet and for eventual drifts (~ 13 parameters), or even other planets.
Our observation need to be spread over two years since the orbital frequencies we expect are usually of order months to years. Our pilot observations show a departure (green line) compared to theoretical expectations (light green box), which will be resolved by spreading data over two years. We require observations on 40 systems to ensure a probability $> 99\%$ of success, with our most pessimistic occurrence rate.
All our targets are observed in a similar fashion, in order to prevent any observer's biases. We will obtain 1800s exposures, sufficiently long to reach the adequate precision required to meet the sensitivity curve in Fig. 1a. Accounting for a 300s overhead per exposure, we require: 40 x 30 x (1800s + 300s) = 700 hours. Dividing this by 23 systems observable in winter (runs A&C; 10 hr/night) and 17 systems observable in summer (runs B & D; 8 hr/night), **we obtained a total of 77.5 nights**. (78)

9a. Calibration Request:

Standard Calibration

10. Report on the use of ESO facilities during the last 2 years

Several members of the team have lead ESO programmes. Some are still on-going. PI Triaud has led several successful proposals to study the Rossiter-McLaughlin effect on planets and binary systems. Since P85 overall the Rossiter programme has produced 32 papers, two more are in preparation. We revealed that planets occupy a large range of orbital inclinations, something we hope to detect on circumbinary stars too. Triaud led a circumbinary planet pilot programme on HARPS in P99. The observations just finished are will be reported in a publication soon (Triaud et al. in prep). Triaud had a DDT programme approved on UVES on a binary (P99). The data is currently under analysis. Several members have had GTO and Large Programmes on HARPS for a number of years, leading to dozens of publications.

11. Applicant's publications related to the subject of this application during the last 2 years

Triaud, A.H.M.J. et al. 2017, A&A accepted: The EBLM Project IV. Spectroscopic orbits of over 100 eclipsing M dwarfs masquerading as transiting hot-Jupiters

Martin, D.V. 2017, MNRAS 467, 1694: Transit probability of precessing circumstellar planets in binaries and exomoons

von Boetticher et al. 2017, A&A 604, L6: The EBLM project. III. A Saturn-size low-mass star at the hydrogen-burning limit

Martin, D.V. 2017, MNRAS 465, 3235: Circumbinary planets - II. When transits come and go

Triaud, A.H.M.J. et al., 2017, MNRAS 467, 1714: Peculiar architectures for the WASP-53 and WASP-81 planet-hosting systems.

Correia, A.C.M. et al. 2016, CeMDA 126, 189: Secular and tidal evolution of circumbinary systems

Martin, D.V. & Triaud, A.H.M.J. 2016, MRNAS 455, L46: Kozai-Lidov cycles towards the limit of circumbinary planets

Martin, D.V. et al. 2015 MNRAS 453, 3554: No circumbinary planets transiting the tightest Kepler binaries.

Triaud, A.H.M.J. et al. 2015, MNRAS 450, 2279: WASP-80b has a dayside inside the T-dwarf range.

Martin, D.V. & Triaud, A.H.M.J. 2015, MNRAS 449, 781: Circumbinary planets - why they are so likely to transit.

Armstrong, D. J. et al. 2014, MNRAS 444,1873: On the abundance of circumbinary planets.

Martin, D.V. & Triaud, A.H.M.J. 2014, A&A 570, A91: Planets transiting non-eclipsing binaries.

Triaud, A.H.M.J. 2014, MNRAS 439, L16: Colour-magnitude diagrams of transiting Exoplanets - I. Systems with parallaxes.

Gillon et al. 2014, A&A 562, L3: WASP-103 b: a new planet at the edge of tidal disruption

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
AC	J0035-69	00 35 40	-69 48 52	17.5	12.38			
AC	J0040+01	00 40 02	+01 05 40	17.5	11.397			
AC	J0042-17	00 42 34	-17 17 53	17.5	10.348			
AC	J0048-66	00 48 21	-66 09 37	17.5	11.631			
AC	J0055-00	00 55 14	-00 07 54	17.5	10.963			
AC	J0228+05	02 28 09	+05 35 48	17.5	10.237			
AC	J0310-31	03 10 23	-31 07 36	17.5	9.339			
AC	J0345-10	03 45 13	-10 58 24	17.5	11.197			
AC	J0353-16	03 53 55	-16 57 15	17.5	10.524			
AC	J0418-53	04 18 05	-53 48 05	17.5	11.454			
AC	J0425-46	04 25 32	-46 13 08	17.5	10.979			
AC	J0500-46	05 00 33	-46 11 21	17.5	12.034			
AC	J0526-34	05 26 39	-34 36 59	17.5	11.182			
AC	J0550-15	05 50 02	-15 36 01	17.5	10.922			
AC	J0608-59	06 08 32	-59 32 28	17.5	11.731			
AC	J0627-67	06 27 31	-67 46 19	17.5	11.533			
AC	J0650-34	06 50 29	-34 36 18	17.5	10.292			
AC	J0700-30	07 00 42	-30 43 09	17.5	11.953			
AC	J0925-03	09 25 54	-03 18 19	17.5	10.33			
AC	J0954-23	09 54 53	-23 19 56	17.5	10.714			
AC	J0954-45	09 54 59	-45 17 26	17.5	9.832			
AC	J1008-29	10 08 34	-29 35 58	17.5	10.61			
AC	J1021-17	10 21 45	-17 13 28	17.5	10.247			
BD	J1201-36	12 01 47	-36 26 49	17.5	10.819			
BD	J1301-37	13 01 01	-37 58 41	17.5	12.094			
BD	J1304-37	13 04 08	-37 00 17	17.5	11.465			
BD	J1305-31	13 05 06	-31 26 13	17.5	11.94			
BD	J1328+05	13 28 15	+05 35 39	17.5	11.669			
BD	J1403-32	14 03 40	-32 33 27	17.5	12.081			
BD	J1525-36	15 25 29	-36 24 17	17.5	11.7			
BD	J1540-09	15 40 09	-09 29 02	17.5	10.998			
BD	J1928-38	19 28 59	-38 08 27	17.5	11.207			
BD	J2040-41	20 40 42	-41 31 59	17.5	11.497			
BD	J2046+06	20 46 44	+06 18 10	17.5	9.867			
BD	J2054-32	20 54 38	-32 07 24	17.5	11.273			

Following targets moved to the end of the document ...

Target Notes: A note about the targets and/or strategy of selecting the targets during the run. For APEX runs please remember to specify the PWV limits for each target under Additional info in the table above.

12a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

None of our targets have been observed with HARPS previously to our knowledge, except five of them in the course of two proposal: 1) was a pilot survey which triggered this programme (PI Triaud, 099.C-0138), and 2) was a programme whose primary goal was to observe the Rossiter-McLaughlin effect (PI Triaud, 092.D-0261). Finding circumbinary planets requires a timespan longer than the couple of months those existing data span (at most). Those older data will complement our survey and will slightly increase our sensitivity on these systems.

12b. GTO/Public Survey Duplications:

Past proposals (PI Helminiak, prog.ID 087.C-0012 & 089.C-0415) proposed a similar science case on HARPS in the past. However they observed double line binaries, which are known to contaminate each others radial velocity solution at a level where it becomes hard to detect gas-giants. Having received only few nights, they could only observe a few systems on a limited number of epochs. In addition, their observations were not designed to detect planets near the stability limit, where we now know, is located a pile-up of objects. We could not find results from these observations.

13. Scheduling requirements

1. Run Splitting

Run	splitting
A	4,30w,4,30w,4,30w,4,30w,4
B	4,30w,4,30w,4,30w,4,30w,4
C	4,30w,4,30w,4,30w,4,30w,4
D	3,30w,4,30w,4,30w,4,30w,3

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
101	HARPS	A	spectro-ObjA(B)	HARPS
102	HARPS	B	spectro-ObjA(B)	HARPS
103	HARPS	C	spectro-ObjA(B)	HARPS
104	HARPS	D	spectro-ObjA(B)	HARPS

4b. Co-investigators:

...*continued from Box 4a.*

A.	Collier Cameron	School of Physics and Astronomy,University of St. Andrews,UK
A.	Santerne	Laboratoire d'Astrophysique de Marseille (LAM),F
R.	Mardling	Monash University,,AU
A.	Correia	Observatorio Astronomico da Universidade de Coimbra,P
F.	Pepe	Observatoire Astronomique de l'Universite de Geneve,CH
D.	Ségransan	Observatoire Astronomique de l'Universite de Geneve,CH
S.	Gill	Astrophysics Group,School of Physics and Geographical Sciences,Lennard-Jones Laboratories,Keele University,UK

12c. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
	...continued from box 12.							
BD	J2101-45	21 01 02	-45 06 57	17.5	10.5			
BD	J2122-32	21 22 58	-32 29 17	17.5	10.628			
BD	J2207-41	22 07 28	-41 48 56	17.5	10.394			
BD	J2215+02	22 15 11	+02 59 14	17.5	11.929			
BD	J2217-04	22 17 58	-04 51 53	17.5	12.184			