SAAO 1.0m telescope time application
Observations of transiting planets in preparation for JWST
Low-mass eclipsing binaries from SuperWASP

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1 Application summary

We apply for four weeks of observing time on the SAAO 1.0 m telescope with STE4 CCD in order to perform two projects: obtaining light curves of planetary transits and of eclipses of low-mass eclipsing binaries. Both projects are time-critical in that they require observations of specific targets at specific times. The projects use the same observational approach – time-series high-precision photometry. They can therefore be efficiently scheduled by running in tandem during an observing run using one telescope, instrument, and observer. We have included both projects in this application following advice from Ramotholo Sefako. We now present the two science cases (colour-coded) and the technical case. Figures and references follow on subsequent pages.

2 Observations of transiting planets in preparation for JWST

The discovery of extrasolar planets (Mayor & Queloz, 1995) was one of the major scientific achievements of 20th century astronomy and a big step towards answering some of the fundamental questions of popular science: how many planets exist, what are their characteristics, and how do they form and evolve? Of the many planets now known, those that transit their host star are the most valuable because they are the only ones whose masses and radii, and thus densities and surface gravities, are directly measurable (e.g. Torres et al., 2008). Perhaps the most important of this subset is the class of *transiting hot Jupiters* – gas giants which orbit very close to their parent star and thus have extended and highly irradiated atmospheres. Their formation mechanisms are still unclear, and their large sizes remain unexplained by current theories (e.g. Baraffe et al., 2014).

Transiting hot Jupiters are very well suited to studies of the atmospheres of extrasolar planets. Many have low surface gravities and high temperatures, so have large atmospheric scale heights. This enables the use of *transmission spectroscopy* to measure the opacity in their atmospheres, and its variation with wavelength, allowing the detection of scattering processes and molecular absorption (Seager & Sasselov, 2000; Sing et al., 2016).

The next big steps in transmission spectroscopy will be enabled by the NASA James Webb Space Telescope (JWST) which is scheduled for launch in late 2018. It will host four scientific instruments, which will together be able to perform transmission spectroscopy over 600 nm to 28 μm. A large fraction of hot Jupiters will be characterised in detail using these instruments, which will be pushed beyond their design limits. Based on extensive experience with both the *Hubble* and *Spitzer* space telescopes, it is expected that it will take time to understand the characteristics of each instrument and find the optimal observing approach. This has led to the creation of an Early Release Science program which aims to obtain all possible types of observations at the start of JWST science observations, so the community can develop the techniques required to observe and analyse the data (Stevenson et al., 2016). A set of six southern transiting planets, all discovered using the SuperWASP telescope at SAAO, have been identified as excellent targets for this program; WASP-62 is most important as it is the only one in the JWST continuous viewing zone. It is vital to study these planets in advance, in order to understand their physical properties, and to determine the precise orbital ephemerides which are crucial for scheduling the JWST observations (Stevenson et al., 2016).

We ask for observing time to obtain light curves of transits of these objects. The light curves will be modelled with the JKTEBOP code (Southworth 2013) and the results will be used to determine the full physical properties of the systems, via the *Homogeneous Studies* approach (Southworth 2008, 2012). Part of the work will be performed by PhD students, and will be published quickly in order to help the JWST planning.

3 Low-mass eclipsing binaries from SuperWASP

The goal of NASA's upcoming Transiting Exoplanet Survey Satellite mission is to observe bright planet hosting stars over 27 day intervals. Newly discovered planets will have short periods and consequently habitable planets, with liquid water existing at the surface, will only be found around late-type stars such as M dwarfs (Triaud et al., 2013). This has been exemplified with the recent discovery of at least two exoplanets in the habitable zone in the TRAPPIST-1 system (Gillon et al., 2016; Bolmont et al., 2016).

To fully understand any planets we must first characterise the host stars. Obtaining stellar mass and radius is usually done by comparing observable parameters (e.g. $T_{\rm eff}$ and luminosity) to theortical evolutionary models. Despite the abundance of low-mass stars in the galaxy, the relation between their mass, radius and composition is poorly understood (Gómez Maqueo Chew et al. 2014) so obtaining their masses and radii from comparison to evolutionary models leads to biases. The radii of low mass stars are typically underestimated by 3% to 5%, which has been attributed to enhanced magnetic activity and inhibition of convection (Morales et al., 2010). Interestingly this is seen in both single interferometric measurements and eclipsing binary systems, making it unclear whether orbital and rotational synchronization can be blamed (Spada et al. 2013).

We have therefore started to empirically calibrate mass-radius-[Fe/H] relations using low-mass eclipsing binary (EBLM) systems discovered by the SuperWASP project. These comprise an F/G/K-dwarf primary star and a much fainter K/M star companion, and are found in large numbers by transit surveys because they mimic true transiting planetary systems. Over 100 EBLMs have been identified by SuperWASP and been studied spectroscopically with the CORALIE échelle spectrograph. We therefore have measurements of the orbit, $T_{\rm eff}$ and chemical composition of the primary star in each system. The SuperWASP light curves are sufficient to show that they are eclipsing, but not to measure their masses and radii to useful accuracy. We therefore require high-quality photometry to measure the contact points of the eclipses, and thus their full physical properties, in exactly the same way as we do for transiting planetary systems. We aim for a precision of a few percent in the masses and radii of the component stars (Torres et al., 2010). Analysis of a large sample of EBLM systems will allow us to calibrate empirical mass-radius-composition relations for low mass stars (e.g. Enoch et al., 2010; Southworth 2011), which will ease the dependence of exoplanetery properties on stellar evolution models. This work forms the bulk of the PhD thesis of one of the applicants, and will lead to timely publication as we already have the spectroscopic observations needed for the analysis of these systems.

4 Technical case

Both projects require high-precision photometric observations of individual stars during specific time intervals, in order to measure the depth, duration and shape of transits. The durations of the transits are typically 3–4 hours so a full night is needed to observe each transit plus the out-of-transit observations which are vital for establishing the baseline flux of the star. The depths of the transits range from 1% to 5%, so photometry at the mmag level is needed to measure them to high precision. This is achievable by the method of *telescope defocussing* which has been used extensively by our group (e.g. Fig. 2; Southworth et al., 2009ab, 2010, 2014, 2016; Mancini et al., 2014abc, 2016) on telescopes of size 1.0 m to 2.2 m. This approach distributes the flux from a point source over 100–1000 pixels, allowing long exposure times to be used so less time is lost to CCD readout. The results are insensitive to seeing changes and flat-fielding errors, and have low Poisson and scintillation noise (Southworth et al., 2009a). We have found that it is possible to obtain a photometric precision of 0.6 mmag per point using a typical 1.2 m telescope and have also successfully used it with the SAAO 1.0 m (see Fig. 1).

We will use the STE4 CCD on the 1.0 m telescope, which has a big enough field of view for at least one good comparison star to be available for all of our main targets. We will observe using broadband filters at red-optical wavelengths (Bessell RI, Gunn riz) where our target stars produce a lot of flux and the telescope throughput is good. Data reduction will be performed using the DEFOT software designed for defocussed photometry (Southworth et al., 2009a, 2014) and will include flat-fielding, debiassing, aperture photometry, and calculation of differential magnitudes versus an optimal ensemble comparison star.

Scheduling these observations is not straightforward as most of our target stars have a full observable transit on only a small fraction of nights. Our time request has therefore been built around the six highest-priority targets: those for the first project. We identified every observable transit for these systems in the Sept-Dec 2016 period, and found two time intervals of 11 and 7 consecutive nights when many transits were observable (Oct 5–15 and Dec 1–7). We then extended these time periods to cover full weeks beginning on Wednesdays (Oct 5–18 and Nov 30 to Dec 13, in order to fit in with the usual scheduling pattern for the SAAO telescopes. The additional nights will be used to observe targets from the second project, which has many more target stars and so observable transits on almost all nights. There are a few nights where no target from either project is transiting, and we will use these to observe other transiting planetary systems of interest (primarily published and unpublished WASP planets). All nights will therefore be used for observations. Scheduling plots of the transits for project 1 are shown in Fig. 3.

5 Figures

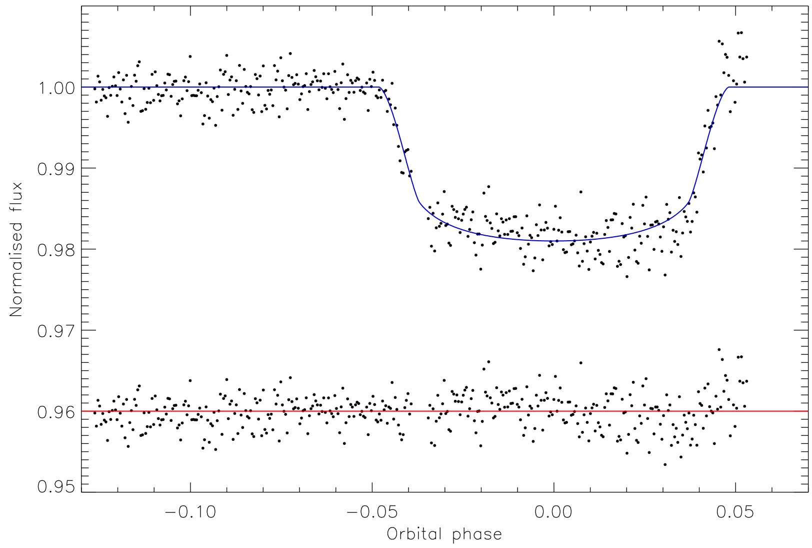

Figure 1: Light curve of a transit in the planetary system WASP-121, obtained by our group on 30th January 2016, using the SAAO 1.0 m telescope and the telescope-defocussing technique. The points represent the observations and the blue line shows the best-fitting model obtained with the JKTEBOP code. The residuals of the fit are shown at the bottom of the figure. The scatter in the light curve is 2.3 mmag, and the weather conditions were non-photometric with very variable seeing. The exposure time was 30 s and the observing cadence 48 s. Whilst the quality of this photometry is just about adequate for our projects, we would expect to obtain a big improvement (scatter 1 mmag or less) in better observing conditions and by defocussing further.

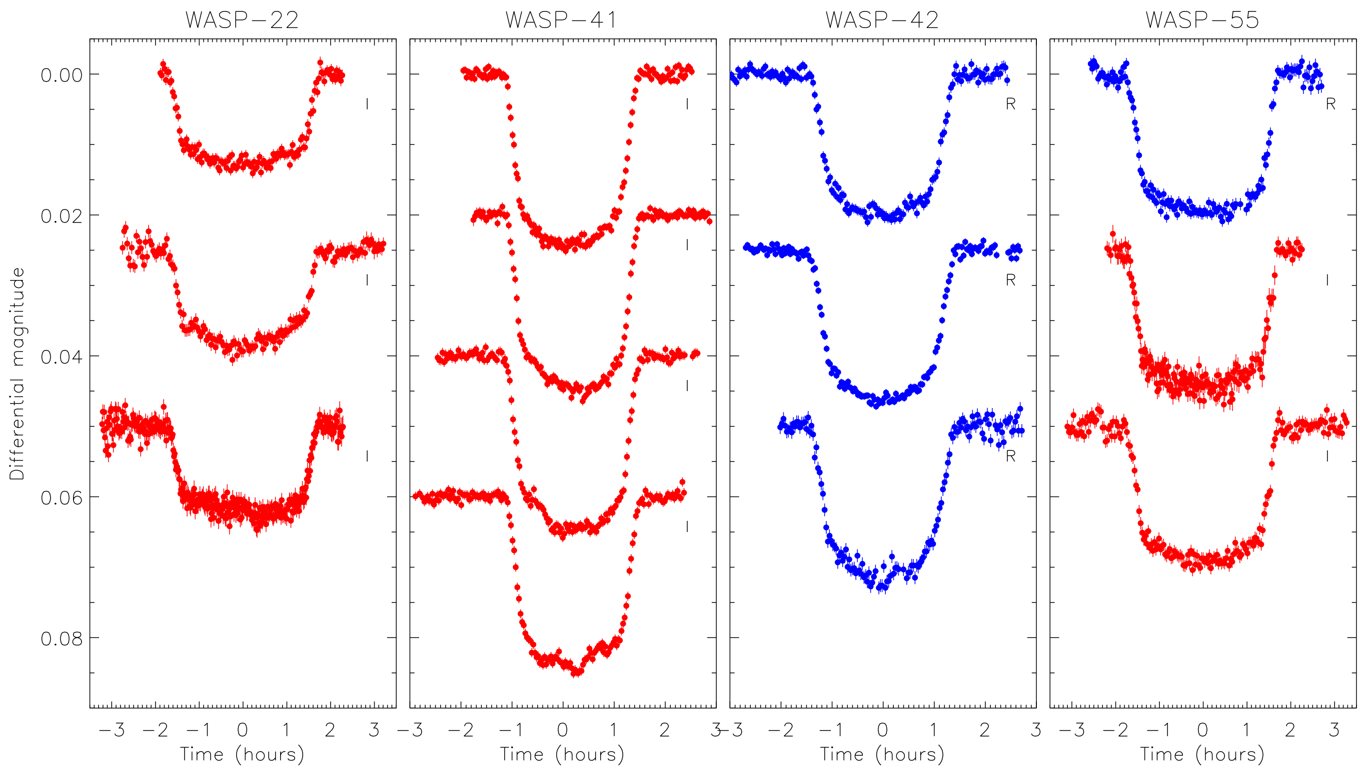

Figure 2: Example transit light curves from the 1.5 m Danish Telescope at ESO La Silla and the telescope-defocussing method (Southworth et al., 2016). A total of 13 transits are shown for four planetary systems, and the filter used is labelled (Cousins R for blue points, Cousins I for red points). Starspots are visible as small upward blips during transits in the WASP-41 system.

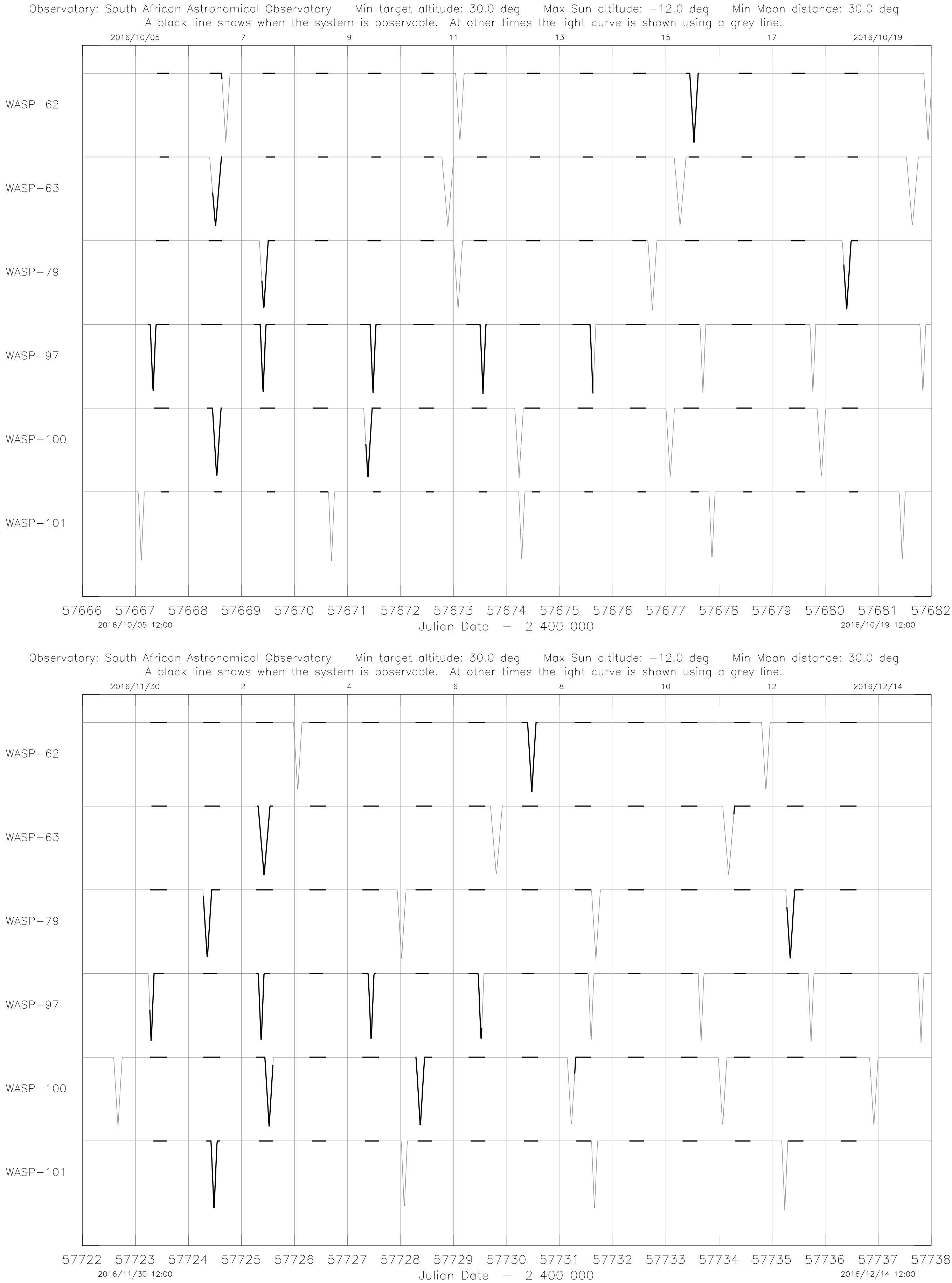

Figure 3: Diagram of the light curves of the six transiting planetary systems for the first project. Bold lines indicate when the object is observable (including moon position) and thin lines indicate the remaining times. The top panel is for the first proposed observing run (5–18 October 2016) and the bottom panel for the second proposed observing run (30 November to 13 December 2016).

6 References

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7 Target list

Project 1: **Observations of transiting planets in preparation for JWST**

Target	RA(J2000)	Dec (J2000)	Orbital period	Transit duration	Transit depth	Magnitude
WASP-62	05 48 33.59	−63 59 18.3	4.411953 d	0.1588 d	1.4%	$V = 10.2$
WASP-63	06 17 20.74	−38 19 23.8	4.37809 d	0.2225 d	0.7%	$V = 11.2$
WASP-79	04 25 29.02	−30 36 01.5	3.6623866 d	0.1661 d	1.3%	$V = 10.0$
WASP-97	01 38 25.04	−55 46 19.5	2.072760 d	0.1076 d	1.5%	$V = 10.6$
WASP-100	04 35 50.32	−64 01 37.3	2.849375 d	0.160 d	0.8%	$V = 10.8$
WASP-101	06 33 24.26	−23 29 10.2	3.585722 d	0.113 d	1.1%	$V = 10.3$

Project 2: **Low-mass eclipsing binaries from SuperWASP**

The characteristics of the targets are similar to those in the table above, but there are many more targets (approximately 100) so we do not reproduce them here.

Backup observing list

A few nights will have no observable transits for either of the two projects above. In this case we will observe transits of planetary systems in the southern hemisphere. We will prioritise planets which have been found by the SuperWASP consortium, of which we are members, but have not yet been the subject of a publication. For published planets we will take the details from the TEPCat catalogue maintained by the PI (see Southworth 2011 and `http://www.astro.keele.ac.uk/jkt/tepcat/`). As of 13 May 2016, TEPCat contains the physical and observable properties of a total of 159 transiting planets in the southern hemisphere.