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Characterising EBLMs from SuperWASP-North

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Abstract. Precise measurements of mass and radius for low mass stars ($< 0.4 M_{\odot}$) are not common as their intrinsic faintness makes accurate measurements difficult. Low mass eclipsing binaries (EBLMs) containing a M dwarf or brown dwarf eclipsing a F/G/K star, can give us precise system properties independent of stellar models, allowing us to test and improve these models. We present EBLMs identified in Super-WASP North data. We characterise these stellar systems using Super-WASP photometry and follow up photometry and spectroscopy.

Key words. low mass eclipsing binaries – photometric survey – radial velocities

1. Introduction

1.1. Low mass stars

Low mass stars ($< 0.4 M_{\odot}$) have far fewer precise measurements of bulk properties than higher mass stars since accurate measurements of these properties, such as mass and radius, are more difficult due to the intrinsic faintness of low mass stars. Characterising low mass stars can help us to investigate what mass (and radius) distribution separates stars, brown dwarfs and planets and their relative frequencies. Better understanding of M dwarf hosts and their effect on habitable zone exoplanets also requires a good understanding of their fundamental properties.

Low mass eclipsing binaries (EBLMs) are composed of an M dwarf or brown dwarf eclipsing a higher mass F/G/K star. As the properties of the brighter, higher mass star are easier to better constrain, observing low mass stars in EBLMs can give us precise system properties independent of low mass stellar models. These observations can test the accuracy of stellar evolutionary models, such as Baraffe et al. (2015), for single stars and improve our understanding of their properties.

1.2. SuperWASP

SuperWASP is a wide-field photometric survey which began surveying the sky for transiting exoplanets in 2004. Each telescope stares at the same field for a season, looking for the characteristic periodic small dip (~1%) in a star's brightness indicative of its exoplanet transiting across its face.

Late M dwarf stars and large exoplanets can have similar radii, therefore when they pass in front of their host star of a given size, they produce similar depth transits. Indeed, when SuperWASP began, objects with transit depths indicating radii greater than $1.6\,R_{Jup}$ were categorised as candidate EBLMs. The discovery of the hot Jupiter WASP-12b with radius $2\,R_{Jup}$ (see Fig. 1) illustrated that some exoplanets can be larger than stars. To distinguish between large exoplanets and small stars, the EBLM project began.

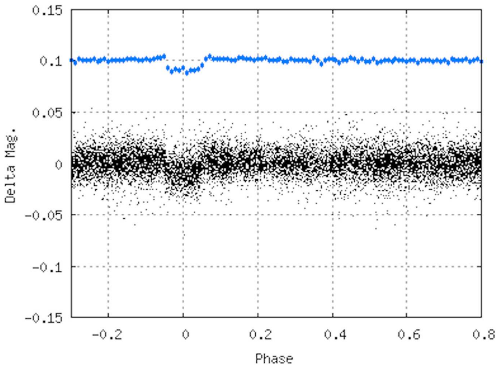

Fig. 1. Light-curve for hot Jupiter planet WASP-12b, which has a radius of 2 R_{Jup} from SuperWASP.

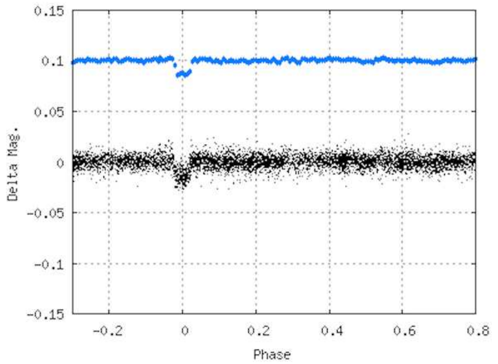

Fig. 2. Light-curve for an example EBLM from SuperWASP.

We present EBLMs identified in Super-WASP North data. *Gaia* Data Release 2 (Gaia Collaboration 2018) can identify only the primary star in these systems. In the following sections we outline how we are characterising these stellar systems using Super-WASP photometry and follow-up photometry and spectroscopy, as well as catalogue information.

2. Observations

2.1. SuperWASP

SuperWASP-North is a wide-field exoplanet transit survey, consisting of 8 × 20 cm telescopes located at the Roque de los Muchachos Observatory on La Palma. Photometric survey fields are observed at 2 × 10 seconds roughly every 8 minutes. Data is reduced and processed, including running a box least-squares (BLS) algorithm based on Kovács et al. (2002) to find transit-like events. Full details about the mission and data handling can be found in Pollacco et al. (2006) and Collier Cameron et al. (2006). The output from BLS are then vetted by eye with accompanying information about the star to identify candidate exoplanets.

During vetting, objects were flagged as candidate EBLM systems if they had secondaries with calculated radii larger 1.6 R_{Jup} and no visible secondary eclipse. For the EBLM project, candidate EBLMs were selected for spectroscopic vetting / recon spectroscopy.

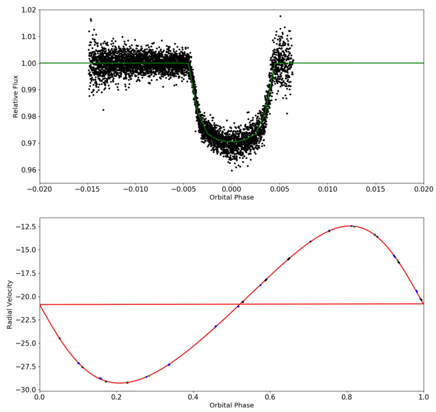

Fig. 3. Example fitted models from ellc+rv modelling. The top subplot shows the light-curve around the transit with the fitted model shown in green. The bottom subplot shows radial velocity measurements across the entire orbit with the red line the fitted model.

2.2. Recon spectroscopy with IDS

The Intermediate Dispersion Spectrograph (IDS) is a medium resolution long-slit spectrograph on the 2.5m Isaac Newton Telescope at the Roque de los Muchachos Observatory on La Palma. IDS is capable of detecting the few kms^{-1} shift due to the gravitational pull of an orbiting brown dwarf or late M dwarf. Based on the SuperWASP photometry, can-

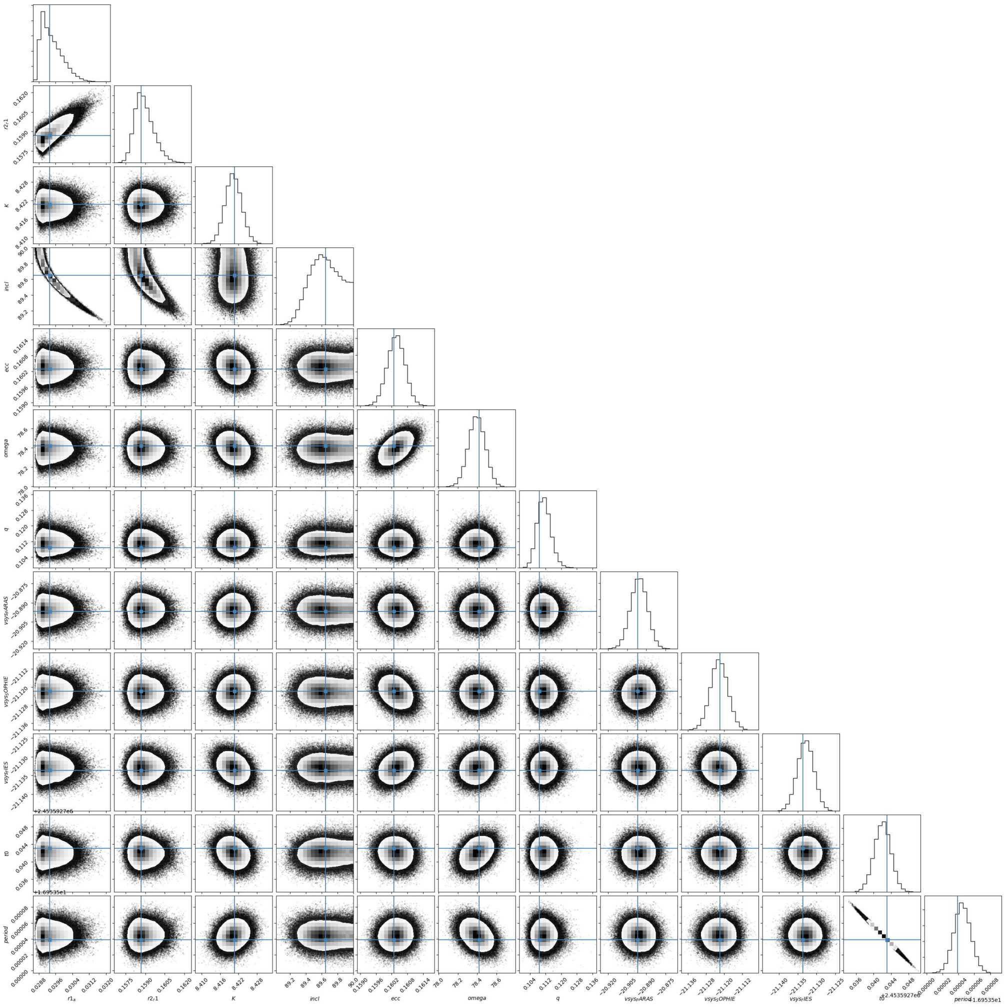

Fig. 4. Example corner plot from ellc+rv modelling produced for the fitted model shown in Fig. 3.

didate EBLMs were observed at quadrature phases (0.25 and 0.75) as this is the maximum semi-amplitude radial velocity (RV) shift for non-eccentric orbits. Recon spectroscopy were also taken using the CORALIE, SOPHIE, FIES and CAFE spectrographs.

The spectra were reduced, extracted, and wavelength calibrated. The extracted 1D spectra were cross-correlated using appropriate stellar masks to obtain radial velocity measurements.

2.3. Follow-up spectra

Targets for which both quadratures were observed and which showed visible shifts in radial velocity were observed further with the same instruments listed above. Further spectra were used to calculate radial velocities and constrain the orbit, with lower mass and more interesting objects prioritised.

2.4. Follow-up photometry

Follow-up photometry was performed on EBLM objects where necessary to confirm the transit, resolve blended objects and provide higher precision light-curves for modelling. Follow-up photometry was performed using the Near Infra-red Transiting ExoplanetS telescope (NITES) 0.4m telescope in La Palma (McCormac et al. 2014) which has a Finger Lakes Instrumentation (FLI) Proline 4710 CCD camera. NITES employs the DONUTS auto-guiding algorithm to guide with sub-pixel precision (McCormac et al. 2013). Aperture photometry was performed on the data, using non-varying comparison stars selected by hand, and the aperture size chosen to minimise the out of transit rms flux.

3. Data

From a sample of approximately 800 objects flagged as candidate EBLMs in SuperWASP, 528 systems have been observed through recon spectroscopy. Of these, 358 systems have been identified as single lined binaries (SB1s) and 170 as double or triple lined spectroscopic binaries (SB2/3s). Among the SB1s, 337 systems have at least two spectral points. The primary stars in SB1s cover a range of spectral types from early F to late K dwarfs. As SuperWASP targets bright stars, the primary stars are brighter than V magnitude of 13.

3.1. Modelling with ellc+rv

The binary star light-curve model code ellc (Maxted 2016) can simultaneously model the light-curves and radial velocity data (ellc+rv). The code was extended to enable it to fit the data from multiple radial velocity instruments and light-curve colours at the same time. Quadratic limb-darkening constants input into ellc+rv were calculated using the Limb Darkening Toolkit (LDTk) (Parviainen & Aigrain 2015). Starting parameters to describe the orbit, primary star and limb-darkening coefficients along with the data are modelled using ellc+rv then iterated over a user specified number of steps using emcee (Foreman-Mackey et al. 2013). Outputs are the parameter chains, the light-curve and radial velocity model, corner plot and best fitting parameters with uncertainties. See Fig. 3 for a light-curve and radial velocity model for an example EBLM and Fig. 4 for the associated corner plot. Parameters of the low mass secondary, including mass, radius and orbital distance are calculated from the best fitting model parameters.

4. Conclusions

We have presented the EBLM project, which is characterising low mass eclipsing binaries in the SuperWASP-North data. EBLMs were identified as transiting candidates in the photometric data before being confirmed by recon spectroscopy using instruments such as IDS. Further spectroscopic data was collected to calculate radial velocities across the secondary star's orbit, and follow up photometry was performed where higher precision light-curves were needed. System parameters were characterised by simultaneously modelling the light-curves and radial velocity data using ellc+rv.

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