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Observation and Modelling of Transits and Starspots in the WASP-19 Planetary System

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Abstract. We have developed a new model for analysing light curves of planetary transits when there are starspots on the stellar disc. Because the parameter space contains a profusion of local minima we developed a new optimisation algorithm which combines the global minimisation power of a genetic algorithm and the Bayesian statistical analysis of the Markov chain. With these tools we modelled three transit light curves of WASP-19. Two light curves were obtained on consecutive nights and contain anomalies which we confirm as being due to the same spot. Using these data we measure the star's rotation period and velocity to be 11.76 ± 0.09 d and 3.88 ± 0.15 km s^{-1}, respectively, at a latitude of 65°. We find that the sky-projected angle between the stellar spin axis and the planetary orbital axis is $\lambda = 1.0^\circ \pm 1.2^\circ$, indicating axial alignment. Our results are consistent with and more precise than published spectroscopic measurements of the Rossiter-McLaughlin effect.

Keywords. stars: planetary systems, stars: spots, stars: rotation, stars: individual (WASP-19).

1. Introduction

At present there are three main ways to measure the rotation period of a star. The first is to use photometric rotational modulation over many months or years (Hall 1972). The second method uses radial velocity mesurements to find the projected rotational velocity, $v \sin I$, which gives a lower limit on v and thus the rotation period. The third method, presented by Silva (2008), is the idea of measuring the rotation period of a star by using a transiting planet crossing a starspot. This opens up the possibility to allow the rotation period of a star to be found from two sets of photometry from a 2m-class ground-based telescope.

After observing three light curves of WASP-19, we discovered that two of our datasets contained a starspot anomaly. Starspots can affect the shape of a transit (Silva 2010) and if not correctly modelled can lead to biased measurements of the system parameters. To achieve our original goal to obtain precise measurements of the system properties we decided to develop a new model capable of modelling both the transit and starspots simultaneously. With a precise known position of the spot at two close but distinct times we would then be able to calculate the obliquity of the system and compare this to the values found from measurement of the Rossiter-McLaughlin effect (Hellier *et al.* 2011, Albrecht *et al.* 2012). This would also allow us to measure the rotation period of the star and compare it to the value found by photometric modulation (Hebb *et al.* 2010).

2. Overview

To obtain accurate measurements of the system and spot parameters we created an IDL computer code to model both the planetary transit and starspots on the stellar

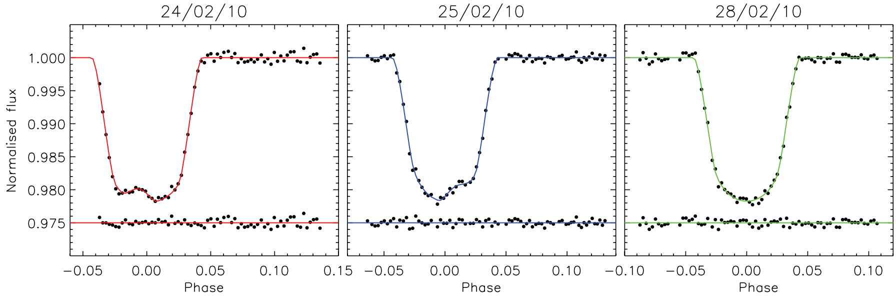

Figure 1. Transit light curves and the best-fitting models. The residuls are displayed at the base of the figure.

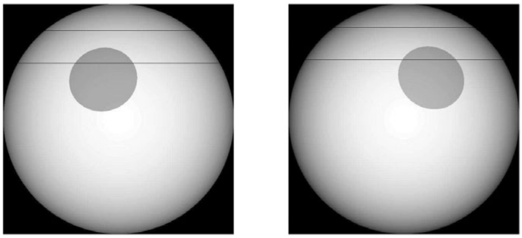

Figure 2. Representation of the stellar disc, starspot and transit chord for the two datasets containing spot anomalies.

surface. PRISM† (Planetary Retrospective Integrated Star-spot Model) uses a pixellation approach to create the modelled star on a two-dimensional array in Cartesian coordinates. This makes it possible to model the transit, limb darkening and starspots on the stellar disc simultaneously. We then decided to develop a new optimisation algorithm, which combined the global optimisation power of the Genetic Algorithm but is also able to perform Baysian statistics on the solutions. We call this new algorithm GEMC (Genetic Evolution Markov Chain). GEMC is based on a Differential Evolution Markov Chain (DE-MC) put forward by Ter Braak (2006).

3. Results and Discussion

The final photometric parameters for the WASP-19 system are given in Table 1 and are weighted means plus 1-σ uncertainties of the results from the three individual fits. Fig. 1 compares the light curves to the best-fitting models, including the residuals. From the positions of the starspot at the time of the transits on the nights of 2010/02/24 and 2010/02/25 (Fig. 2), it is possible to calculate the rotational period of the star and the sky-projected spin orbit alignment of the system using simple geometry. The spot has travelled $24.5° \pm 0.3°$ in 1.020 ± 0.001 orbital periods, giving a rotational period of $P_{\rm rot} = 11.8 \pm 0.1$ d at a latitude of 65°. Combining this with the stellar radius, we calculate the latitudinal rotational velocity of the star to be $v_{(65°)} = 3.9 \pm 0.2$ km s^{-1}. The positions of the spot finally yield a sky-projected spin orbit alignment of $\lambda = 1.0° \pm 1.2°$ for WASP-19.

We have applied PRISM to three transit light curves of the WASP-19 planetary system. Two of the light curves are of consecutive transits and show anomalies due to the occultation of a starspot by the planet. The measured latitudes and longitudes of the

† Available from http://www.astro.keele.ac.uk/∼jtr

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Table 1. Combined system and spot parameters.

Parameter	Symbol	Value
Radius ratio	r_p/r_s	0.143 ± 0.001
Sum of fractional radii	$r_s + r_p$	0.330 ± 0.002
Linear LD coefficient	u_1	0.43 ± 0.05
Quadratic LD coefficient	u_2	0.22 ± 0.01
Inclination (degrees)	i	79.0 ± 0.2
Spot angular radius (degrees)	$r_{\rm spot}$	15.1 ± 0.1
Spot contrast	$\rho_{\rm spot}$	0.77 ± 0.01
Stellar rotation period (d)	$P_{\rm rot}$	11.8 ± 0.1
Projected spin orbit alignment (degrees)	λ	1.0 ± 1.2

spot during the two transits were used to calculate the rotation period of the star and the sky-projected obliquity of the system. Our model assumes that the spot anomaly can be represented by a circular spot of uniform brightness. It is quite likely that the "spot" is in fact a group of smaller spots with lower contrasts, but investigation of this puts extreme demands on data quality and quantity which are practically impossible to satisfy for ground-based observations.

We find a rotation period of $P_{\rm rot} = 11.76 \pm 0.09$ d at a latitude of 65°, whereas Hebb *et al.* (2010) found a $P_{\rm rot}$ of 10.5 ± 0.2 d from rotational modulation of the star's brightness over several years. The latter value comes from the spot activity over the whole visible surface of the star, whereas our value is for a specific latitude. The difference between these two numbers may therefore indicate differential rotation.

We find a rotational velocity of $v_{(65^\circ)} = 3.88 \pm 0.15\,{\rm km\,s^{-1}}$ for WASP-19 A, which in the absence of differential rotation would yield an equatorial rotation velocity of $v_{(90^\circ)} = 4.30 \pm 0.15\,{\rm km\,s^{-1}}$. Hellier *et al.* (2011) reported a spectroscopic measurement for $v \sin I$ of $5.0 \pm 0.3\,{\rm km\,s^{-1}}$ and assumed this value represented the equatorial velocity. They included it as a prior when modelling the Rossiter-McLaughlin effect, finding a final value of $v \sin I = 4.6 \pm 0.3\,{\rm km\,s^{-1}}$. This last measurement is appropriate for the latitude at which the planet transits, and may differ from ours due to the effect of starspots on radial velocity measurements taken during transit.

We find a sky-projected obliquity of $\lambda = 1.0^\circ \pm 1.2^\circ$ for WASP-19, which is in agreement with but more precise than published values based on observations of the Rossiter-McLaughlin effect [$4.6^\circ \pm 5.2^\circ$, Hellier *et al.* (2011); $15^\circ \pm 11^\circ$, Albrecht *et al.* (2012)].

This work shows how transit photometry can be used to determine the rotation period and sky-projected obliquity of an active star, by using a planet.

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