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Exploring Eclipsing Binaries, Triples and Higher-Order Multiple Star Systems with the SuperWASP Archive

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Abstract. The Super Wide Angle Search for Planets (SuperWASP) is a whole-sky high-cadence optical survey that has searched for exoplanetary transit signatures since 2004. Its archive contains long-term light curves for ~30 million 8–15 V magnitude stars, making it a valuable serendipitous resource for variable star research. We have concentrated on the evidence it provides for eclipsing binaries, in particular those exhibiting orbital period variations, and have developed custom tools to measure periods precisely and detect period changes reliably. Amongst our results are: a collection of 143 candidate contact or semi-detached eclipsing binaries near the short-period limit in the main sequence binary period distribution; a probable hierarchical triple exhibiting dramatic sinusoidal period variations; a new doubly-eclipsing quintuple system; and new evidence for period change or stability in 12 post-common-envelope eclipsing binaries, which may support the existence of circumbinary planets in such systems. A large-scale search for period changes in ~14000 SuperWASP eclipsing binary candidates also yields numerous examples of sinusoidal period change, suggestive of tertiary companions, and may allow us to constrain the frequency of triple systems amongst low-mass stars.

1. Introduction

The Super Wide Angle Search for Planets (SuperWASP; Pollacco et al. 2006) is, as its name indicates, primarily a sky survey searching for exoplanetary transits. However, several of its characteristics also suit it well for the study of variable stars, especially eclipsing binaries: it has an 8–15 V magnitude range, a fairly long (7–9 years) time base, and a usefully high cadence (6–40 minutes). Almost whole-sky coverage is achieved, and the archive contains some 30 million light curves of which perhaps 1 million are significantly variable. The initial motivation for our study was to explore this archival resource looking for evidence of orbital period variations in eclipsing binaries; this was certainly achieved, and a number of serendipitous discoveries of unusual systems were also made in the course of the research program. Here we will outline some of our analytical techniques and our main results of relevance to this conference.

2. Methods

Techniques for detecting and quantifying the orbital periods and period changes of eclipsing binary candidates from their SuperWASP light curves were developed and improved over the course of the project (Lohr et al. 2012, 2013b, 2014b). The most reliable and precise approach found for the large quantities of often noisy data available here was to fold each full light curve on a range of trial periods and select the period giving the least scatter of points about the mean curve (a form of phase dispersion minimization): this did not require any assumptions to be made about the underlying light curve shape. In addition to a value for the orbital period, this yielded a phase-folded light curve which was used as a template to fit each night of observations in the full curve. The template was adjustable in time, flux and amplitude, allowing optimal measurement of the times of primary eclipse. These observed times of minimum could then be compared with calculated times of minimum (on the assumption of constant period) to produce observed minus calculated ($O - C$) diagrams: a standard tool for detecting and measuring period variation.

3. Results

3.1. Eclipsing Binary Candidates Near the Short-Period Limit

We first focused attention on eclipsing binaries with very short orbital periods, near the well-known but still mysterious limit in the period distribution for main sequence systems, around 0.20 d (e.g., Paczyński et al. 2006). Norton et al. (2011) had found 53 candidates with $P < 20,000$ s in the SuperWASP archive; in the study of Lohr et al. (2012) some of the periods of these were corrected, and period changes were detected in several cases, demonstrating the feasibility of using this data set for measuring orbital period variation. Then, in the subsequent study of Lohr et al. (2013b), the set of such objects was increased to 143, nearly all previously unpublished, and their periods were seen to tail off smoothly as one end of the larger distribution, rather than exhibiting a sharp cut-off: this may help to constrain possible explanations for the short-period limit. Several of these candidates have since been confirmed spectroscopically as binaries, and their parameters determined (e.g., Lohr et al. 2014a); others turned out to be rare and fascinating systems in their own right, as described in the next two sections.

3.2. A Probable Low-Mass Contact Binary in a Triple System

1SWASP J234401.81−212229.1 (J234401) showed an apparent contact binary light curve, with primary eclipses only slightly deeper than secondary ones, and an extremely short period of variation (18,461.64 s). Over the first four years of archive data it exhibited a very dramatic period decrease (Lohr et al. 2012), but subsequent observations by SuperWASP and David Boyd supported a sinusoidal variation in its $O - C$ diagram (Lohr et al. 2013b), with modulating period ~ 4.2 yr. However, SALT spectra for the system did not give any clear indications of binarity and seemed rather to indicate a single mid-K star. In the Lohr et al. (2013a) work we explored a range of possible models to explain these apparently conflicting findings, and favored a triple system containing a low-mass (M+M) contact binary in a 4.2 yr orbit with a much hotter K star, which dominates the spectrum. Recently, Koen (2014) has made multicolor observations and further analysis of J234401, which support our preferred model: notably, the system is bluest during eclipses (when a cool component is obscured), and the light curve amplitude increases with increasing wavelength (since the variation is produced by stars with spectra peaking in the near-infrared). This would appear to be only the second confirmed contact system consisting of two M dwarfs.

3.3. A Doubly-Eclipsing Quintuple System

1SWASP J093010.78+533859.5 (J093010) also initially appeared to be a very short-period contact binary (P = 19,674.47 s), but with significant non-Gaussian data scatter below the main folded light curve; additional eclipses were also visible in the full curve. Upon refolding it on a longer period (112,798.90 s) a second *detached* binary was revealed, and we noted that *Hipparcos* had observed two point sources at this location (TYC 3807-759-1 and TYC 3807-759-2) separated by just 1.″88; in our Lohr et al. (2013b) study we announced this as plausibly the sixth-known doubly-eclipsing quadruple system.

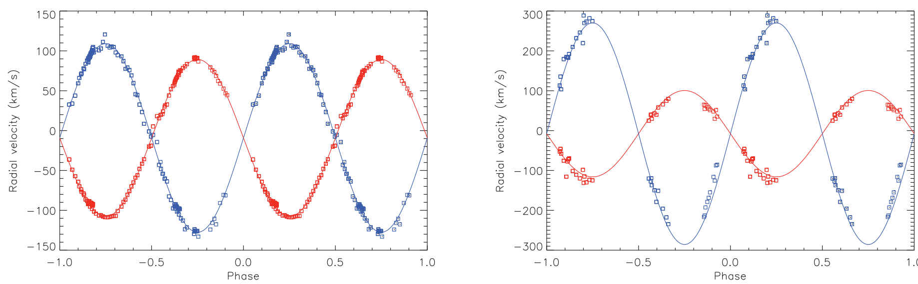

Figure 1.: Radial velocity curves for J093010. *Left:* Detached system, combining our observations with those of Koo et al. (2014). *Right:* Contact system, based on our WHT observations.

Since then, Koo et al. (2014) obtained spectra for J093010, from which they extracted radial velocities for the detached binary; they also noted the presence of an extra, static set of spectral lines, which they interpreted as a probable fifth star. We have independently obtained WHT spectra for each eclipsing system separately, and thus produced radial velocity curves for both the detached and the contact systems (Figure 1), confirming each as a double-lined spectroscopic and eclipsing binary (Lohr 2014). Our spectra confirm the presence of the fifth star, in close proximity to the detached binary; moreover, all five stars exhibit a common systemic velocity (approximately -10 km s^{-1}) and compatible distance estimates (~50–60 pc), providing further support to their interpretation as members of a gravitationally-bound quintuple. Modeling of their combining photometric and spectroscopic data sets also suggests an angle of inclination $i \simeq 89°$ for both binaries: it may be that they lie in the same orbital plane and fragmented from a single protostellar disk.

3.4. Circumbinary Planets in Post-Common-Envelope Systems?

Another set of eclipsing binaries which we have investigated have undergone common-envelope evolution. Such systems, of which the prototype is HW Vir, exhibit distinctive light curves with very well-defined primary eclipses and strong reflection effects, allowing precise determination of their times of light minima and tracking of period changes. Controversially, circumbinary planets have been claimed in many such systems on this basis (Zorotovic & Schreiber 2013). In our Lohr et al. (2014b) paper we reported our study of the 12 systems of this type found in the SuperWASP archive, for which we measured hundreds of new times of minimum, some with uncertainties as small as a few seconds. For HW Vir, we found highly significant evidence of a period increase, which tallied perfectly with the two-planet model of Beuermann et al. (2012); in NY Vir, QS Vir and NSVS 14256825 we found less significant support for proposed period changes. Also, there was significant evidence of period change in ASAS J102322−3737.0, which had not previously been detected. Whether or not circumbinary planets are the cause, our findings strongly support the reality of period variations in at least some eclipsing post-common-envelope systems.

3.5. Multiplicity Everywhere?

Most recently, we have applied our analytical approach to ~14,000 SuperWASP eclipsing binary candidates identified in Payne (2013). Many cases of steady period increase and decrease (revealed by quadratic fits to $O-C$ diagrams) were found for the three light curve-defined classes of eclipsing system (EA, EB, and EW); unexpectedly, all the period change distributions were symmetrical about zero, and very similar in shape.

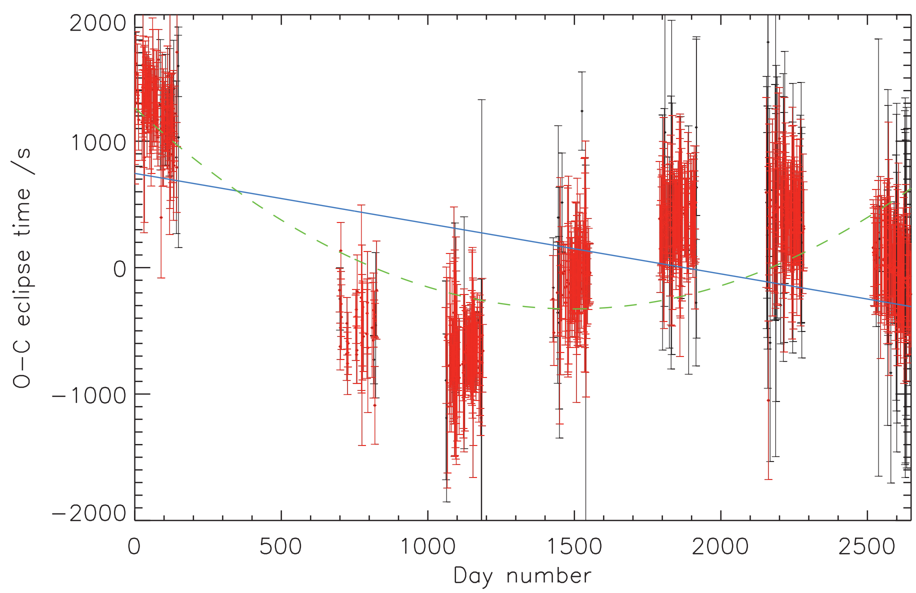

Figure 2.: $O-C$ diagram for a SuperWASP eclipsing binary candidate exhibiting sinusoidal variation. Linear (solid line) and quadratic (dashed line) best fits are over-plotted; neither matches the period variation well.

A number of sinusoidally-varying $O-C$ diagrams were also seen (e.g., Figure 2), and in these may lie an explanation for the symmetrical distributions of steady period changes (Lohr 2014). The majority of apparently quadratic $O-C$ diagrams may in fact be short sections of sinusoidal variations: being equally likely to come from any part of a longer-term sinusoidal curve, they will be detected as apparent steady period increases or decreases in equal numbers. If this is true, and if the majority of such sinusoidal period variations are caused by undetected third bodies (as in Sect. 3.2), we can use these period change statistics to estimate the higher-order multiplicity fraction: ~24% of SuperWASP binaries would be in triples, a number which tallies well with recent estimates by other researchers (Tokovinin 2014a,b; Rappaport et al. 2013).

4. Conclusion

The SuperWASP archive has proved to be a treasure trove of data on eclipsing binaries, triples, and higher-order multiples. We have been able to uncover useful findings about specific sets of objects (very short-period binaries, post-common-envelope systems) and discover rare and informative individual systems (J234401, J093010). We may even be able to draw conclusions about the frequency of triple systems among lower-mass stars in general.

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