Transiting Planets
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Co-ordinated Follow-Up of Transiting Planet Candidates with Robotic Telescope Facilities

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Abstract. There are now several large photometric surveys scanning millions of stellar light-curves for signs of planetary transits. All produce large candidate lists with a high false alarm rate, so that further observations are required to confirm new detections. One such survey, SuperWASP, produced ~150 candidates during the 2007–2008 season. Here we describe our campaign to follow-up 86 of these candidates using the robotic facilities of Las Cumbres Observatory Global Telescope Network and the Tenagra-II robotic telescope in Arizona. The aim of these observations was to eliminate false positives as far as possible ahead of spectroscopic follow-up and to provide additional photometry to help characterise the surviving targets.

1. Introduction

Like all large photometric surveys searching for transiting exoplanets, the SuperWASP Project† (Pollacco *et al.* 2006) must overcome the challenge of identifying these systems from a sample of several million stars. Collier Cameron *et al.* (2007) describes the algorithm used for the automated search, and the selection procedure used to evaluate the results. To date, ~4.14 million stars have been surveyed by this algorithm. Selected objects are visually assessed and catalogue data is used to estimate the stellar parameters and to infer those of the planet. Imaging data from the Digitized Sky Survey, 2MASS (Skrutskie *et al.* 2006) and the Sloan Digital Sky Survey (Abazajian *et al.* 2005) is used to look for close companions. This produces a follow-up list of typically ~150 objects, of which 30–40 are considered top priority planet candidates.

However, experience from several transit hunting surveys leads us to expect that ~90% of these candidates will be false positives (Pont 2007). Obtaining the necessary follow-up observations is a large-scale programme in itself, including 13 photometric and spectroscopic facilities worldwide. The WASP Consortium was awarded time on the high-resolution echelle spectrographs Sophie/Observatoire de Haute Provence-1.93m and Coralie/Swiss 1.2m, La Silla, but ideally we would like to 'pre-filter' our target list and dedicate this time to obtaining radial velocity data for the best targets only.

The use of robotic facilities reduces the manual observing workload of large survey follow-up campaigns, and can allow more flexibility than traditionally block-scheduled telescopes. The Las Cumbres Observatory Global Telescope Network (LCOGT)‡ currently consists of two 2m telescopes (in Australia and Hawaii), supplemented by time on the 0.81m Tenagra-II telescope in Arizona. All three are robotically controlled. We report here on an ongoing programme to provide photometry of transit candidates discovered by SuperWASP.

† www.superwasp.org
‡ www.lcogt.net

Our aim was to get higher resolution photometric follow-up at an early stage in order to resolve the targets from near neighbours blended in SuperWASP frames. The initial run on any target normally employed an "on-off" strategy to produce observations of a partial transit, or rotating through 2–3 targets at 20 min intervals to improve efficiency. If this confirmed the original transit detection, observations were scheduled for complete transits in order to better constrain the system parameters and ephemeris.

2. A Problem of Scale: Robotic Follow-Up of Large Numbers of Candidates

The candidates produced by SuperWASP are distributed over both hemispheres and the full range of RA. A subset of the targets are therefore available for observation at any given time, and we have run a continuous follow-up campaign since August 2007. The target list and ephemerides are constantly refined, both through this programme and observations elsewhere, so the follow-up campaign needs to be flexible and allow the observing schedule to be re-written sometimes only hours before it was due to be carried out.

LCOGT's 2m Faulkes Telescopes North & South (FTN/FTS) are both equipped with 2048×2048 pixel CCD cameras normally used in binned 2×2 mode, giving them a 4.7×4.7 arcmin field of view. The telescopes operate with a dispatch scheduler which repeatedly selects from a database of requested observations throughout each night (Fraser & Steele 2004). Being time dependent, transit observations are normally entered as 'fixed [time] blocks'. However, these facilities are not dedicated to this campaign; they run a number of research programmes, and a significant fraction of the time is used for educational outreach. To minimise disruption to other users while retaining the ability to respond to 'hot' targets on reasonable timescales, we predict the observable transits for the top candidates for each telescope two weeks in advance. The sequence of observations is then added to the database for robotic execution. Observations can still be made at very short notice via a Target of Opportunity override if required.

Complementing LCOGT's developing network, we purchased 100% of the time on the Tenagra-II 0.81m telescope in Arizona† for the 2007–2008 season. This has a SITe 1024×1024 pixel CCD camera with a 14.8×14.8 arcmin field of view. While we ran a number of science programmes during this time, the majority of the time was dedicated to transit candidate follow-up. This telescope is also robotic, controlled by a sequence of instructions submitted via a single file. The schedule was generated on a daily basis and was therefore highly flexible.

3. Summary of Targets Observed

Between August 2007 and May 2008, 86 candidates were observed. Table 1 gives a breakdown of the outcome of follow-up observations for these objects.

This programme has provided data for 11 of the new transiting exoplanets discovered by the WASP survey (see Christian *et al.* (2008), Joshi *et al.* (2008), Hellier *et al.* (2008) & Hebb *et al.* (2008), and Figure 1). As expected, eclipsing binaries accounted for the majority of false positives (20 of the 74 targets analysed so far, 27%) most of which were easily distinguished by follow-up photometry. More difficult to identify were triple systems. One such target initially seemed very promising and our data confirmed the occurence of transits on a 1.18 day period. The target was put forward for spectroscopy,

† www.tenagraobservatories.com

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Table 1. Summary of the nature of candidates originally selected as transiting exoplanet candidates. Eclipsing binary is abbreviated to EB.

No. of objects	Class	No. of objects	Class
11	WASP planets	6	EB blended with constant neighbour
11	Non-variable target blended with EB	12	No photometric variation observed
19	Observations inconclusive	2	Likely triple systems
3	Low-mass eclipsing binaries	12	Data awaiting reduction
10	Surviving candidates		

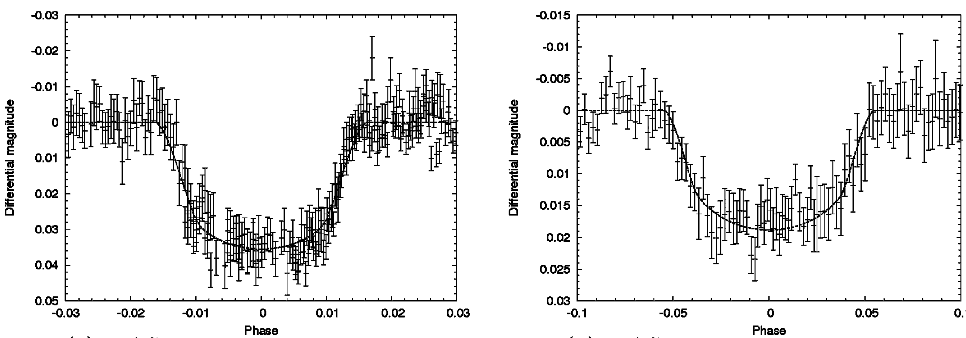
which indicated a dwarf-class host star. However, radial velocity data showed a trend on a much longer period, not correlated with the photometric eclipses. It was concluded that the object is most likely a triple system consisting of a short-period eclipsing binaries with a constant companion in a much longer orbit.

We found that $12/74 = 16\%$ of our targets showed no sign of photometric variation in either the target or any near neighbour despite repeated observations of predicted transits. In these cases, the original detection may have been spurious or the uncertainty in the ephemeris may be sufficient that the transits actually occurred outside the window of follow-up. If the latter is true, then additional data from SuperWASP would help to constrain the ephemeris for later confirmation.

For 19 objects, the data gathered so far has been inconclusive, generally because weather or technical problems resulted in insufficient data being collected. Transit-like signatures have been confirmed for a further 10 stars, which remain on our follow-up list.

4. Discussion

Large photometric surveys searching for time-variable phenomena like SuperWASP inevitably produce a large number of candidates which require follow-up observations. The sheer number of targets and their wide distribution on the sky means it is necessary to use several telescopes in both hemispheres. A network of robotically controlled telescopes gives us an efficient and flexible way to follow-up large numbers of candidates. This season we have used photometry to pre-select the best targets for radial velocity observations, thereby maximising our return from limited time allocations on high-precision spectrographic instruments.



(a) WASP-10 I band lightcurve (b) WASP-12 B band lightcurve

Figure 1. Tenagra lightcurves of two new transiting planets. Data from 2 and 3 nights respectively have been combined here, and placed in bins of 120s in the case of WASP-12b. Theoretical lightcurves generated using the parameters published by Christian *et al.* (2008) and Hebb *et al.* (2008) are superimposed.

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We obtained data on 11 of the new WASP transiting planets. Of the 74 targets analysed, 27% were rejected, and transits could not be confirmed in 16% of cases. However, it was not possible to follow all the candidates (some ~150 objects), and as the selection procedure includes elements of human assessment it is difficult to draw conclusions about the underlying planetary population. Not surprisingly, triple star systems proved to be the most difficult type of false detection to distinguish.

Although the use of robotic telescopes enabled us to run this programme with relatively little manpower compared with conventional follow-up campaigns, much of the workload derived from the planning and scheduling of observations on multiple telescopes. With 18×1m and 24×0.4m telescopes due to join the LCOGT network over the next few years, we need to make this process less human-intensive.

For future seasons, we aim to improve the flexibility of the robotic system and reduce the manual planning work. For instance, we would like to be able to specify a candidate's ephemeris and coordinates and obtain observations from whichever telescope in the network is best able to execute the programme at that time. The network-coordinating software would need to take user-specified criteria into account (such as the transit duration, amount of out-of-transit data required, desired signal-to-noise, filter etc), as well as target visibility, weather conditions at multiple sites on the night and technical specifications (availability of instrument/filters, target brightness .vs. telescope aperture etc). The software must also balance the demands of many competing projects.

Over the next 2 years, LCOGT plan to make medium-resolution spectrographs available on the 2m telescopes, which will complement the new Spectral CCD cameras that should be available by the end of 2008. These will have a larger (~10×10 arcmin) field of view than the current instruments, making it easier to include sufficient comparison stars for differential photometry.

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