A SuperWASP search for additional transiting planets in 24 known systems

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ABSTRACT
We present results from a search for additional transiting planets in 24 systems already known to contain a transiting planet. We model the transits due to the known planet in each system and subtract these models from light curves obtained with the SuperWASP (Wide Angle Search for Planets) survey instruments. These residual light curves are then searched for evidence of additional periodic transit events. Although we do not find any evidence for additional planets in any of the planetary systems studied, we are able to characterize our ability to find such planets by means of Monte Carlo simulations. Artificially generated transit signals corresponding to planets with a range of sizes and orbital periods were injected into the SuperWASP photometry and the resulting light curves searched for planets. As a result, the detection efficiency as a function of both the radius and orbital period of any second planet is calculated. We determine that there is a good (> 50 per cent) chance of detecting additional, Saturn-sized planets in \( P \sim 10 \) d orbits around planet-hosting stars that have several seasons of SuperWASP photometry. Additionally, we confirm previous evidence of the rotational stellar variability of WASP-10, and refine the period of rotation. We find that the period of the rotation is 11.91 ± 0.05 d, and the false alarm probability for this period is extremely low (\( \sim 10^{-13} \)).

Key words: techniques: photometric – planetary systems.

1 INTRODUCTION

1.1 Multiple planet systems
Of the 347 presently known extrasolar planets, 90 are known to reside within multiple planet systems.1 All of these systems, however, have been discovered by radial velocity measurements alone; none of them was discovered via the transit method, nor have any been later discovered to transit their host stars. The study of multiple planet systems enables greater understanding of theories of planet formation and migration, and affords us the opportunity to study planetary dynamics in action, as well as helping us answer fundamental questions such as ‘how common is the Solar system?’.

Planets that transit their host stars allow us to measure fundamental properties such as the planetary radius and remove much of the uncertainty on the value of the planetary mass by constraining the orbital inclination angle. This is just as true for multiple planet systems, and further properties such as dynamical evolution timescales can be measured for transiting systems (Fabrycky 2009).

1.2 Detecting transiting multiple planet systems
It has been noted that, given that there are now in excess of 50 known transiting planets, there is a good chance that at least one of these systems may harbour additional planets which we should be able to detect (Fabrycky 2009). There are three methods for detecting further planets in known transiting systems (Fabrycky 2009), namely (i) searching for transit timing variations (TTV) or variations in other transit parameters; (ii) searching for long-term radial velocity trends and (iii) searching for additional transits.

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1 See http://www.exoplanet.eu, accessed on 2009 May 11.
In a multiplanet system, one planet can have a perturbing effect upon the orbit of a second planet, the effects of which can include small variations in the timings of transits caused by the second planet, such that the transits are no longer spaced periodically (Agol et al. 2005; Holman & Murray 2005). Many searches for further planets have been conducted, and continue to be conducted, using TTV, which has great sensitivity to planets in resonant orbits with the first planet, even if the second planet has an extremely low mass.

It is also possible to infer the presence of additional planets by measuring long-term trends in other transit parameters. For instance, Coughlin et al. (2008) report observed increases in the orbital inclination, transit width and transit depth of Gl 436 b, which may indicate the presence of another planet.

In general, the discovery light curves of transiting planets, such as those produced by SuperWASP (Wide Angle Search for Planets), are of insufficient quality to measure transit timings and other parameters with the required precision to discover additional planets; predicted timing variations, for instance, are typically of the order of seconds or tens-of-seconds. Additional resources must therefore be expended to obtain high-precision light curves.

Secondly, known planets continue to be monitored for long-term trends in the radial velocity data, as is common practice with planets discovered by that means alone. Many longer-period additional planets have been found around stars around which a relatively short-period planet has been discovered by radial velocity measurements. Long-term monitoring of RV systems has yielded planets with periods of several years (the longest such period is 14.3 yr). This too requires a modest expenditure of telescope time in order to obtain radial velocity data points at suitable intervals to detect longer-period planets.

Finally, photometric monitoring of known transiting systems may reveal transits caused by a second planet in the system. The inclination angle of this second planet must be sufficiently similar to that of the first planet, that the second planet can be seen to transit its star as well as the first. This method, unlike the other two, does not necessarily require the allocation of further observing resources; instead the data archives of transit surveys can be searched for such transit signals. Such surveys often observe the same fields for several seasons, and so have a large quantity of data on known transiting systems. In this paper we present results from a search of the data archive of SuperWASP, one such wide-field transit survey (Pollacco et al. 2006).

### 1.3 Detecting transiting multiple planet systems by transit photometry

Only two of the 58 known (to 2009 March) transiting planets have orbital periods, $P$, greater than 10 d (these were both detected initially by radial velocity means and were only later discovered to transit); indeed only six transiting planets have periods longer than 5 d. This is largely due to the selection effects present in wide-field surveys: (i) in general, a relatively large number of transits are required to boost the signal-to-noise ratio sufficiently that the transit may be detected in the presence of correlated (‘red’) noise (Smith et al. 2006). This requirement for many transits leads to the preferential detection of short-period planets that exhibit frequent transits. (ii) The probability that a given planetary system exhibits transits is inversely proportional to the orbital semimajor axis, $a$, and so this again causes a bias towards the detection of short-period planets.

Any additional transiting planet is likely to orbit with a period greater than the currently known planet. Several factors militate against the usual difficulties in detecting long-period ($P > 5$ d) planets, however. Most significantly, the probability that any second planet will transit should be greatly enhanced by the fact that there is already one transiting planet in the system. This is because the orbits of exoplanets in multiple systems are generally predicted to be close to coplanar, because such systems are believed to form from a flat disc in a similar fashion to the Solar system (e.g. Bouwman et al. 2006). In the Solar system, this results in all planetary orbits being coplanar to within a few degrees.

If we assume coplanarity to within $5^\circ$, the probability that the second planet transits is approximately equal to the ratio of the semimajor axes of the inner and outer planets, $a_{in}/a_{out}$ (Fabrycky 2009). This means, for example, the probability of a planet orbiting a solar analogue with a 10-d period is increased from about 5 to around 45 per cent if an inner transiting planet exists with a period of 3 d.

Some previous attempts have been made to detect additional transiting planets. Croll et al. (2007a,b) used the Microvariability and Oscillations of STars (MOST) satellite to place upper limits on the presence of additional transiting planets in two systems (HD 209458 and 189733) known to harbour a transiting exoplanet. They were able to rule out the presence of additional planets larger than about 0.2 $R_J$ orbiting with periods less than 14 d for HD 209458 and planets larger than about 0.15 $R_J$ orbiting with periods less than 7 d for HD 189733.

This paper reports results from an extensive search of archival SuperWASP data for additional transits of stars known to host transiting exoplanets. We provide constraints on the existence of additional transiting planets in such systems.

### 2 OBSERVATIONS

Time series photometry of 24 stars which host transiting exoplanets was obtained by the SuperWASP instruments, which are wide-field, multicamera survey instruments described in Pollacco et al. (2006).

15 of these planets were observed by SuperWASP-N, located at the Roque de los Muchachos Observatory on La Palma in the Canary Islands, and nine by WASP-South, at the South African Astronomical Observatory in Sutherland. The objects observed are the first 18 planetary systems discovered by SuperWASP (with the exception of WASP-9, for which follow-up observations are still ongoing) and seven similar systems discovered by other transiting planet surveys and retrospectively detected in SuperWASP data. Details of all these objects are given in Table 1. SuperWASP has an extensive archive of data on these objects. Many of them have been monitored for several observing seasons, dating back to 2004 in some cases.

### 3 SEARCH FOR ADDITIONAL PLANETS

To search the SuperWASP light curves for additional transits we first take all existing light curves on a particular object from the SuperWASP archive. Several light curves may exist if the star has been observed in several seasons and/or with more than one camera.

A systematic re-analysis of each of these systems was performed using all the photometric data either publicly available or held by the WASP consortium. The transits caused by the known planet were modelled using the Markov Chain Monte Carlo (MCMC) technique described by Collier Cameron et al. (2007a), which uses the analytic model of Mandel & Agol (2002) (see Table 1 for details of the parameters fitted). The resulting fitted parameters are within the joint error bars of the best published parameters. The modelled
transits were then subtracted from the light curves, and the resulting residual light curves concatenated into a single residual light curve for each object.

We then search each of these residual light curves using HUNT1STAR, a modified version of the adapted Box Least-Squares (BLS) algorithm used for routine SuperWASP transit hunting (Kovács, Zucker & Mazeh 2002; Collier Cameron et al. 2006). The HUNT1STAR routine searches the light curve of a single object for transits, and it is able to handle large quantities of photometric data spanning multiple seasons and cameras, with a finely sampled period grid.

The light curves of a total of 24 transiting planet host stars (see Table 1 for the details of these objects) were searched for additional transits with periods of between 5 and 25 d using HUNT1STAR. This lower limit of 5 d was chosen because, with the exception of WASP-8 b with a period of 8.16 d, all of the original planets have periods between 0.9 and 5.0 d, and so have been searched at sub-5-d periods previously. The upper limit of 25 d was chosen after consideration of the length of the observing baselines and because for this period, the orbital inclination angle, \(i\), must be greater than about 88° in order for transits to be exhibited by a Jupiter-sized planet (Fig. 1). The probability of such a planet transiting is around 2–3 per cent assuming nothing about the system, and about 25 per cent if coplanarity to within 5° with a \(P = 3\) d planet is assumed.

A periodogram is produced for each object, and the parameters of the five strongest peaks in the periodogram are refined. The resulting candidates are loosely filtered according to the criteria usually used for SuperWASP planet hunting (Collier Cameron et al. 2006). These criteria are as follows: (i) at least two transits must be detected; (ii) the reduced \(\chi^2\) of the model must be less than 2.5; (iii) the phase-folded light curve must not consist of a high proportion of gaps and (iv) the signal-to-red-noise ratio \(\left(\frac{\text{phot}}{\text{red}}\right)\)\(, \rho_\ast\(\frac{\text{phot}}{\text{red}}\)\) must be less than about 88° in order for transits to be exhibited by a Jupiter-sized planet (Fig. 1). The probability of such a planet transiting is around 2–3 per cent assuming nothing about the system, and about 25 per cent if coplanarity to within 5° with a \(P = 3\) d planet is assumed.

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### Table 1. Planetary systems searched for additional transiting bodies.

| Star  | Obs. | MCMC fitted parameters used to subtract transits from light curves |
|-------|------|---------------------------------------------------------------------|
| WASP-1 | N    | 2.519951, 3998.19239, 0.1551, 0.056, 0.01004, 0.38709, 89.44, 13630 |
| WASP-2 | N    | 2.152227, 9798.60091, 0.0736, 0.729, 0.01742, 1.51264, 84.80, 7941 |
| WASP-3 | N    | 1.846833, 4214.03159, 0.1112, 0.446, 0.01067, 0.59680, 85.20, 5167 |
| WASP-4 | N    | 1.338232, 4387.32776, 0.0881, 0.055, 0.02266, 1.29600, 89.44, 10112 |
| WASP-5 | S    | 1.628428, 4373.99598, 0.0987, 0.314, 0.01180, 0.88028, 86.85, 7503 |
| WASP-6 | S    | 3.361010, 4593.07139, 0.1068, 0.204, 0.02071, 1.70136, 88.96, 14083 |
| WASP-7 | S    | 4.954746, 4133.65826, 0.1555, 0.183, 0.00538, 0.67368, 89.02, 24547 |
| WASP-8 | S    | 8.158754, 4679.33741, 0.1457, 0.332, 0.00871, 0.64012, 84.47, 8593 |
| WASP-10 | N   | 3.092718, 4299.09114, 0.0944, 0.225, 0.02501, 1.89252, 89.70, 8367 |
| WASP-11 | N   | 3.722464, 4473.05587, 0.1066, 0.065, 0.01620, 1.89252, 89.70, 8367 |
| WASP-12 | N   | 1.091423, 4506.79316, 0.1168, 0.393, 0.01390, 0.33880, 82.24, 7233 |
| WASP-13 | N   | 4.352999, 4491.61566, 0.1647, 0.653, 0.00886, 0.28496, 84.92, 8661 |
| WASP-14 | N   | 2.243738, 4555.60866, 0.1145, 0.488, 0.09979, 0.61661, 85.06, 6817 |
| WASP-15 | S   | 3.752087, 4577.19424, 0.1527, 0.456, 0.00953, 0.45322, 86.65, 20442 |
| WASP-16 | S   | 3.118600, 4578.19167, 0.0796, 0.817, 0.01208, 1.13688, 85.00, 12237 |
| WASP-17 | S   | 3.735456, 4566.5221, 0.1777, 0.103, 0.01534, 0.40353, 89.21, 16084 |
| WASP-18 | S   | 0.941453, 4600.88702, 0.0895, 0.336, 0.00871, 0.64012, 84.47, 8593 |
| HAT-P-4 | N   | 0.356544, 4099.10073, 0.1707, 0.040, 0.00616, 0.33246, 89.63, 6546 |
| HAT-P-5 | N   | 2.787765, 3871.02389, 0.1220, 0.488, 0.09979, 0.61661, 85.06, 6817 |
| HAT-P-6 | N   | 3.853041, 3931.62934, 0.1648, 0.054, 0.00568, 0.46098, 89.61, 20718 |
| HAT-P-7 | N   | 2.204799, 4010.72625, 0.1544, 0.029, 0.00258, 0.30042, 89.65, 3647 |
| TrES-2 | N   | 2.470625, 4011.98837, 0.0750, 0.864, 0.01615, 0.95940, 83.46, 6268 |
| TrES-4 | N   | 3.553964, 4063.88015, 0.1218, 0.434, 0.00769, 0.84448, 87.31, 13790 |
| XO-4 | N   | 4.123971, 4477.68782, 0.1488, 0.050, 0.00680, 0.68468, 89.70, 2589 |

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**Figure 1.** Plot indicating the maximum period for a planet to exhibit transits, as a function of orbital inclination angle for a range of stellar masses. The host star is assumed to be on the main sequence and the planet is assumed to be Jupiter sized.
apply more strict filtering since we have a small number of objects, so the risk of false positives is small.

4 RESULTS OF SEARCH FOR ADDITIONAL PLANETS

Of the five best peaks for each of the 24 planets (120 peaks in total), 75 pass the criteria outlined in Section 3, but our initial rejection criteria lean strongly towards retaining candidates.

As we are dealing with a small number of objects, we choose not to apply further cuts on, for example, signal-to-noise ratio, but instead visually inspect all 24 periodograms and all 120 phase-folded light curves. The periodograms produced for each of the 24 stars were inspected for any strong peaks indicative of a genuine transit, and the phase-folded light curves were checked for transit-like signals. Most of the objects do not display any noteworthy periodogram peaks; Fig. 2 is a typical such periodogram, whereas Fig. 3 is a periodogram typical of a genuine transiting planet.

None of the phase-folded light curves displays any transit-like signal.

Five phase-folded light curves were also plotted for each object, corresponding to each of the five strongest peaks in the periodogram. These were inspected for signs of a transit at phase 0, but no such signals were observed, even in the handful of objects that exhibit at least one reasonably strong periodogram peak.

4.1 WASP-10

Although a strongish peak at about 12 d is observed in the periodogram for WASP-10 (Fig. 4), no transit is seen in the corresponding phase-folded light curve. This peak is less well-defined than the typical peak produced by planetary transits (Fig. 3). Instead, we attribute the peak to stellar rotation, the period, $P_{\text{rot}}$, of which is known to be about 12 d (Christian et al. 2009). We confirm the stellar rotation hypothesis by fitting a sine curve of the form $\delta + A \sin(\omega t + \theta)$, where $\omega = 2\pi / P_{\text{rot}}$ to the data (Fig. 5). The best-fitting parameters for data taken in SuperWASP-Ns 2004 and 2006 observing seasons are given in Table 2. We find the same period
of rotation (11.95 d) in both seasons of data, but both the phase of rotation and the amplitude of the variability differ between the two seasons. We also compute the auto-correlation function (Edelson & Krolik 1988) of the data; the period determined by this method is 11.84 d.

Using a generalized Lomb–Scargle periodogram, as described in Zechmeister & Kürster (2009), we are able to calculate the false alarm probability for the signal detected by sine fitting. Despite our light curve consisting of 8546 points, because of red noise the effective number of independent data points, \( n_{\text{eff}} \), is significantly smaller. To calculate \( n_{\text{eff}} \), the individual nights of data are shuffled, destroying the rotation signal, but maintaining the red noise. By assuming the highest peak in the resulting periodogram has a probability of 0.5, we calculate \( n_{\text{eff}} = 949 \). The number of independent frequencies is calculated to be 1135, according to the approximation of Cumming (2004). Using these values, and equation (24) of Zechmeister & Kürster (2009), we calculate the false alarm probability to be \( 3.8 \times 10^{-13} \).

This extremely low probability confirms the reality of this variation, as does the fact that very similar periods were detected in different seasons of data, and with different methods. Taking the mean of all the periods detected, we conclude that the star rotates with \( P_{\text{rot}} = 11.91 \pm 0.05 \). This variability is likely to be caused by starspots; such variability is not unusual amongst K dwarfs.

5.2 Searching for injected transits

Each of the 15 000 light curves generated for each object is searched for transits by HUNT1STAR, in exactly the same way as were the real data (Section 3). The detection efficiency for a planet of a given size and orbital period is determined by the fraction of transits recovered for planets of those characteristics.

Whilst we visually inspected the periodograms and five best light curves of each of the 24 planets when searching the real data (Section 4), this is clearly an unfeasible proposition for 15 000 light curves per object. Instead, for light curves identified as candidates by HUNT1STAR, we require that the injected period, or an alias thereof, and the injected epoch of mid-transit are successfully recovered in at least one of the five best periodogram peaks. To do this, we define the statistic

\[
\eta = \frac{|P_{\text{meas}} - P_{\text{inj}}|}{P_{\text{inj}}},
\]

where \( P_{\text{meas}} \) and \( P_{\text{inj}} \) are the orbital periods measured by HUNT1STAR, and injected into the light curves, respectively. We then require \( \eta < 0.001 \) (corresponding to a detection at the injected period), or 0.4995 < \( \eta \) < 0.5005 or \( -0.0005 < \eta^* < 0.0005 \), where \( \eta^* = \eta_{\text{nint}} - \eta \) (corresponding to detections at an alias of the injected period). These thresholds were designed to encapsulate clearly defined populations of objects clustered around \( \eta = 0, \eta = 0.5 \) and \( \eta = 1, 2, \ldots \). Furthermore, we require that \( \Delta t_0 \leq 0.10 \) d, where \( \Delta t_0 = |t_{\text{inj}} - t_{\text{meas}}| \), and \( t_{\text{inj}} \) and \( t_{\text{meas}} \) are the injected and measured epochs of mid-transit, respectively.

Periodograms and phase-folded light curves for several of the injected transits detected in this manner were inspected in the same fashion as the real data (Section 3), in order to ensure that these objects could have been detected without the prior knowledge of the orbital period. The periodogram and recovered light curve of one such injected transit are shown in Fig. 6.

5.3 Results of simulations

5.3.1 WASP-1

The results of our simulations of extra planets in the WASP-1 system are presented in a series of two-dimensional cuts through the parameter space (Figs 7 and 8). Fig. 7 shows detection efficiency plotted against the radius of the simulated additional planets for a
An example of an artificial transit which is successfully recovered in our simulations. Shown are the HUN1STAR results from transits corresponding to a planet with $P = 15.100$ d and $R_p = 0.85 R_J$, which were injected into the WASP-4 light curve. The planet is detected with $P = 15.10138$ d in the strongest peak of the periodogram (upper panel). The light curve, folded on the recovered period using the recovered epoch of mid-transit, exhibits a clear transit at phase $= 0$ (lower panel).

Variety of orbital periods, whereas in Fig. 8, detection efficiency is shown as a function of orbital period for a range of orbital periods.

The full data set is shown as a contour map in Fig. 9, although the results from the models with periods of 7.957 and 17.957 d are excluded as they are very close to an integer number of days. The sharp drops in detection efficiency observed at these periods (Fig. 8) are manifestations of the well-known 1 d alias phenomenon, which can cause either a sharp reduction or sharp increase in detection ability at periods which are almost exactly an integer number of days (e.g. Smith et al. 2006).

5.3.2 Other systems

Similar simulations were conducted for several of the 24 systems which were searched for additional transits in Section 3. Contour plots of the same type as Fig. 9 were also produced for these systems, although not all of them are shown here for reasons of space. Our ability to detect additional planets in these other systems is very similar to that for WASP-1; there are variations in detection efficiency, but this correlates with the length of the original light curve. There are more data on WASP-1 than most of the other objects – 13 630 data points spanning the 2004, 2006 and 2007 observing seasons. At the other extreme is HAT-P-4, which has a significantly shorter SuperWASP light curve, comprising just 6546 data points, a few hundred of which are from 2006, with the rest from 2007. The contour plot for HAT-P-4 is shown in Fig. 10, where it can be seen that the detection efficiency is poorer, particularly at relatively long periods, than for WASP-1 (Fig. 9).
The four systems are HIP 14810, Ups And, HD 187123 and HD 217107; and \( R \sim 398 \), \( \sin i = i > 0.2 \) \( M_J \), suggesting a radius large enough to be detected. None of these systems contains further planets with periods conducive to detection by means of transits; the second planet from the star orbits with \( P > 95 \) d in each of the four cases.\(^2\) In other words, there is currently no multiple planet system of the kind we have demonstrated we are able to detect at present with SuperWASP known by RV studies. This does not, of course, mean that such systems do not exist, or that we should not look for them, especially given the low expenditure and potentially high reward involved.

7 CONCLUSIONS

We conducted a search for additional planets, with periods between 5 and 25 d, orbiting 24 stars known to harbour a transiting hot Jupiter, using SuperWASP photometry to search for additional transits. No planets were detected, so in order to place upper limits on the existence of such planets, we performed Monte Carlo simulations of planets of various sizes, and with various orbital periods. The results of these simulations suggest that, for objects like WASP-1 with three seasons of SuperWASP photometry, we have a good chance (>50 per cent) of detecting Saturn-sized \( (R_S = 0.843 \, R_J) \) planets out to about 10 d, and a sporting chance of detecting such planets with longer periods (there is an ~20 per cent chance of detecting a Saturn analogue in a 20-d orbit). These detection thresholds improve with increasing planet radius (up to about 1.2 \( R_J \)), and are lower for stars, like HAT-P-4, with fewer data.

We are able to detect planets larger than about Saturn size, and with periods up to ~20 d with reasonable efficiency. As expected, the main factor affecting detectability is the time span of the light curve used to search for additional transits.

7.1 Future prospects

As our simulations (Section 5.3) demonstrated, the longer the span of the light curve, the greater our sensitivity to longer-period planets. As transit surveys continue to observe some of the known planets, our ability to detect additional transits in these systems will increase. Another possibility for increasing the number of available photometric data points is to share data between transit surveys, as suggested by Fleming et al. (2008).

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\(^2\) The four systems are HIP 14810, Ups And, HD 187123 and HD 217107; the second planets in these systems orbit with periods of 95, 241, 3810 and 4210 d, respectively.
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