Transit detection limits for sub-stellar and terrestrial companions to white dwarfs

F Faedi, R West, M R Burleigh, M R Goad and L Hebb

1 Department of Physics and Astronomy, University of Leicester, Leicester, LE1 RH7 UK
2 School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS UK
E-mail: *ff20@star.le.ac.uk

Abstract. The SuperWASP project is a ground-based ultra wide angle search for extra-solar planetary transits that has successfully detected 15 previously unknown planets in the last two years. We have used SuperWASP photometric data to investigate the transit characteristics of and detection limits for brown dwarfs, gas giants and terrestrial companions in orbit around white dwarfs. The relatively small size of a white dwarf host star (approximately 1 Earth radius), implies that any sub-stellar or gas giant companion will completely eclipse it, while terrestrial bodies smaller than the Moon will produce relatively large (> 1%) transits, detectable in good S/N light-curves. We performed extensive simulations using SuperWASP photometric data and we found that for Gaussian random noise we are sensitive to companions as small as the Moon. Our sensitivity drops in the presence of co-variant noise structure, nevertheless Earth-size bodies remain readily detectable in relatively low S/N data. We searched for eclipses and transit signals in a sample of 174 WASP targets, resulting from a cross-correlation of the McCook & Sion catalogue and the SuperWASP data archive. This study found no evidence for sub-stellar or planetary companions in close orbits around our sample of white dwarfs.

1. Introduction
The SuperWASP project is a Wide Angle Search for transiting Extra-solar Planets, which consists of two completely robotic telescopes, SuperWASP-North (La Palma, Canary Islands, Spain) and SuperWASP-South (Sutherland, South Africa). Each telescope comprises eight f/1.8 Canon lenses each with a 2048×13.5μm pixels CCD, giving a field of view of 7.8 degrees square for each camera. The instruments cyclically raster the sky in a series of fields centred on the current local sidereal time and spaced by 1 hour in right ascension to obtain time series of images with typical sampling rate of 8-10 minutes. SuperWASP is the most successful ground-based transit survey with 15 previously unknown extra-solar planets detected in the last two years. More information on the project can be found in Pollacco et al. (2006) and on-line at http://www.superwasp.org/.

The transit technique involves searching for periodic dips in stellar light-curves due to the orbital revolution of a transiting planet, blocking a fraction of the stellar light. The planet transit probability \( P_{tr} \) is directly related to the stellar and planetary radii \( R_\star, R_{pl} \) and the semi-major axis of the orbit \( a \) by \( P_{tr} = (R_\star + R_{pl})/a \). Therefore, only planets with their orbital plane aligned within a few degrees to the line of sight have their transit visible. For a given planetary radius, the transit depth \( \delta \) is proportional to \( (R_{pl}/R_\star)^2 \). Thus, planets orbiting main-
sequence solar-type stars have extremely shallow transits, about $10^{-2}$ magnitudes for a giant planet and $10^{-4}$ magnitudes for an Earth-size planet. A strong advantage over main sequence star primaries is offered by white dwarf stars. White dwarfs (WD) are compact degenerate objects, with approximately the same radius as the Earth, and represent the final stage of evolution of main-sequence stars with masses $\leq 8 M_\odot$ (i.e. $\sim 97\%$ of all stars in our galaxy). Any sub-stellar or gas giant companion in orbit around a white dwarf will completely eclipse it, while bodies as small as the Moon will have relatively large transit depths ($\sim 3\%$), assuming that such systems survive the later stages of stellar evolution. Sub-stellar companions to white dwarfs are rare ($<0.5\%$, e.g. Farihi et al. 2005). Only one wide binary system GD165 (Becklin and Zuckerman, 1988), and two detached non-eclipsing, short-period white dwarf+brown dwarf (BD) systems are currently known, GD1400 (Burleigh et al. 2008 in preparation, orbital period $\sim 10$ hours) and WD0137-349 (Maxted et al. 2006, orbital period $\sim 116$ min). The latter is the lowest mass object ($\sim 50 M_{\text{JUP}}$) known to have survived the common envelope (CE) phase of stellar evolution. These systems remain difficult to identify either as infra-red excesses or through radial velocities measurements. The detection of more such systems will allow us to place observational upper limits on the mass of sub-stellar companions that can survive CE evolution. For example, can Hot Jupiters survive their parent star's evolution to a white dwarf? The detection of a significant number of eclipsing WD+BD binary systems might help uncover the hypothesised population of 'old' cataclysmic variables (CV) in which the companion has been reduced to a sub-stellar mass (e.g. Patterson 1998; Littlefair et al. 2003). These systems are undetectable as X-ray sources and difficult to identify in optical and infra-red surveys. The first such system was finally confirmed by Littlefair et al. (2006), although not through a direct infra-red spectroscopic detection of the brown dwarf companion.

Several theoretical studies discuss post-main sequence evolution of planetary systems and show that planetary survival is not beyond possibility (Duncan and Lissauer 1998; Debes and Sigurdsson 2002; Burleigh et al. 2002; Villaver and Livio 2007). Observations indicate that planets in wide orbits can survive stellar evolution (see Sato et al. 2003 and Silvotti et al. 2007). Moreover, Mullally et al. (2008) found convincing evidence of a $2 M_{\text{JUP}}$ planet in a 4.5 year orbit around a pulsating white dwarf. If confirmed, this will show that planets can indeed survive the death of their parent star. Short-period planetary companions to white dwarfs may seem less likely. Villaver and Livio (2007) suggest that planets in orbit within the reach of the red giant’s envelope will either evaporate or in rare cases, will accrete mass and become a
close, low-mass companion to the star. Nevertheless, the recent detection of silicate-rich dust discs around a growing number of white dwarfs at orbital radii up to $\sim 1 R_\odot$ (e.g. Reach et al. 2005, Farhi et al. 2007, 2008; Jura 2003) suggests that asteroids and larger objects can migrate into such orbits during the final stages of solar system evolution, perhaps because of dynamical instabilities (Debes and Sigurdsson 2002).

In §2 we discuss the characteristics of the transit signals, the parameter space investigated and our detection method. In §3 we analysed a sample of 174 WDs in the superWASP archive. Finally in §4 we discuss our conclusions.

2. Characteristics of the transit signal

A transit signal is described by its duration, its depth and its shape. The known transiting extra-solar planets show signals characterised by an ingress, a flat bottom and an egress, with durations between 2-3 hours and depths of about 1% (see for example Cameron et al. 2007). Our simulated transit events have been modelled assuming circular orbits and fixed stellar parameters. We considered a typical 1 Gyr old Carbon core white dwarf of mass 0.6 M$_\odot$ and radius of $\sim 0.013 R_\odot$. We investigated transits for planets ranging from the Moon size to Jupiter and/or a brown dwarf (which have approximately the same radius), with orbital periods in the range $\sim 2$ h - 15 days (i.e. $\sim 0.003$ - 0.1 A.U.). For this choice of parameters our simulated transits show very short durations ($\sim$1 to 32 min) and very deep transit signals ($\sim$3-100% depth). Figure 1 shows the transit probability and duration for our choice of parameters. Figure 2-left panel shows the transit depth in the same parameter space as Figure 1.

2.1. Synthetic SuperWASP light-curves

SuperWASP light-curves are well sampled light-curves of $\sim 120 - 150$ days/season, taken with a sampling rate of $\sim 8$-10 minutes. To create our set of synthetic data we used the time sampling of SuperWASP light-curves from a frequently observed field of 2004 observing season. Due to our choice of parameters and the SuperWASP observing strategy the injected transit signals appear very deep, of very short durations and with no visible points during ingress or egress. Figure 2 right panel, shows an example of two simulated transit light-curves. Top panel: shows the synthetic light-curve of a hypothetical eclipsing WD+BD binary system with an orbital period of $P \sim 116$ min similar to WD0137-349 (Maxted et al. 2006) (which itself does not show eclipses). The lower panel shows the simulated transit light-curve for a rocky body of the size of the Earth in a $\sim 5$ h orbit.

2.2. Detecting transit signals

To recover the transit signals injected in our set of synthetic light-curves we used a Box Least Square (BLS) algorithm, see Kovács et al. 2002. The BLS utilises the anticipated squared shape of the transit signal and it performs least square fits of step functions to the light-curve, after folding at several trial periods. To better account for the shape of our set of synthetic data we used the BLS with a grid of fixed trial durations $D_{tr} = 1, 2, 4, 8, 16, 32$ min. This covers our transit durations for orbital periods between $\sim 2$ h and 15 days (see Figure 1). For each trial period a $\Delta \chi^2$ is evaluated where $\Delta \chi^2$ is the improvement in the fit $\chi^2$ when compared to that of a constant light-curve $\chi_0^2$ (see Collier Cameron 2006 for more details). Therefore the $\Delta \chi^2$ is proportional to the $S/N$ value of the transit event $\Delta \chi^2 = (S/N)^2$ and $S/N$ is given by:

$$S/N = \frac{\delta}{\sigma_{tr}} \sqrt{N_{tr}}$$  

Where $\delta$ is the transit depth, $\sigma_{tr}$ is the rms of the in-transit points and $N_{tr}$ is the number of points in transit. Because planetary detections are strongly affected by the signal-to-noise value
of the transit event (see Pont et al. 2006 and Collier Cameron 2006) we defined the BLS power spectra in terms of the $S/N$ value of the transit. For each trial period we evaluate the signal detection efficiency (SDE) (Kovács et al. 2002) as:

$$SDE = \frac{S/N_{\text{peak}} - \langle S/N \rangle}{\sigma_{S/N}}$$  \hspace{1cm} (2)

Where $S/N_{\text{peak}}$ is the $S/N$ at the highest peak, $\langle S/N \rangle$ is the average, and $\sigma_{S/N}$ is the standard deviation over the frequency band tested. A detection is represented by the highest peak in the BLS power spectrum. We assigned a statistical significance to the highest peak in the periodogram by testing the BLS response to pure noise. This allowed us to set a detection threshold which we used to define our set of empirical criteria for successful detection. A transit was considered successfully recovered if a peak in the BLS power spectrum was within 0.005 day of the correct (inserted) period and at least 7.3$\sigma$ above the average level of the BLS power spectrum.

The results of our simulations show that for bright white dwarfs ($V \sim 12$) in the presence of Gaussian random noise we are sensitive to objects as small as the Moon. For fainter white dwarfs, we are sensitive to increasingly larger radius rocky bodies. In the presence of covariant noise structure in the data our detection sensitivity is reduced. Nevertheless, Earth size objects remain detectable in low signal-to-noise data. Supported by these results we have investigated a sample of 174 white dwarfs brighter than $V \sim 15$ for which we have SuperWASP data.

3. Searching for transit signals in real SuperWASP data

Our white dwarf sample consists of all objects resulting from a cross-correlation of the SuperWASP data archive and the McCook & Sion catalogue (2006). We only consider objects with more than $\sim 600$ photometric points (equivalent to $\sim 11$ observing nights, for a night of $\sim 8$ hour and sampling cadence of $\sim 8$-10 min). We considered data with multi-season observations (from 2004 to 2008) in order to increase our S/N (see equation 1) and thus our detection probability. The sample of 174 WASP targets has been searched for transits and eclipses using the BLS algorithm. In addition we have inspected the data by eye, individually, for

![Figure 2](image-url)
each light-curve. Transits studied in this work can have durations as short as 1 minute, this might correspond to an individual point, dropped periodically, in a SuperWASP light-curve. Our key result is that we find no evidence of sub-stellar or smaller companions. A detailed discussion of our results can be found in Faedi et al. 2009 (in prep.).

4. Conclusions
We have investigated the transit characteristics and detection limits for sub-stellar and terrestrial companions around white dwarfs. For our chosen range of orbital periods (≈ 2 h - 15 d) and companion sizes (Moon - Jupiter/BD) the simulated transit events appear extremely different from the transit signals due to known extra-solar planets around solar-type stars. Due to the small radii of white dwarfs (≈ 1 R⊕), transits have very short durations and appear extremely deep (100% for gas giants and any body ≥ 1 R⊕). We have investigated our ability to detect transits in SuperWASP light-curves of white dwarfs. We found that for Gaussian random noise we are sensitive to Moon size companions in orbit around a V ∼ 12 white dwarfs. For fainter white dwarfs we are sensitive to increasingly larger radius rocky bodies. Our sensitivity is reduced in light-curves dominated by covariant noise structure. Nevertheless, Earth-size companions remain detectable in low signal-to-noise light-curves. We then analysed a sample of 174 white dwarfs in the SuperWASP data archive for transits and eclipses using a slightly modified BLS routine. We found no evidence for sub-stellar or smaller companions in the sample of 174 WDs. Extensive details on the simulations, the detection algorithm and an interpretation of our null result can be found in Faedi et al. 2009 (in prep.).

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