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The SuperWASP exoplanet transit survey

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Abstract. SuperWASP (Wide Angle Search for Planets) uses robotic installations on La Palma (Canary Islands, Spain) and at Sutherland (South Africa) to survey the sky for transiting exoplanets. At each site, there is an instrument consisting of eight 200 mm camera lenses (0.11 m aperture) backed with Andor e2v CCDs, arranged on a single equatorial fork mount. WASP is responsible for the discovery of 109 transiting exoplanets to date (70 of which have been announced in published papers); more than any other ground-based survey.

Besides reviewing the instrumentation and observing strategy, we briefly outline the motivation for such a survey and discuss the place of WASP in the context of similar surveys. We also describe the planet discovery process and the impact of our discoveries on the exoplanets field. The science impact of WASP is not, however, limited to exoplanets; we also summarise some of the non-exoplanet science (including asteroseismology, binary stars, and comets) that has resulted from WASP data.

Finally, we discuss the future of WASP and of small aperture, ground-based exoplanet surveys in general, including the forthcoming Next Generation Transit Survey (NGTS).

Key words: planetary systems – stars – Instrumentation: photometers – Techniques: photometric

1. Introduction

After the discovery of the first exoplanet orbiting a main-sequence star (Mayor & Queloz, 1995) it was several years before the first transiting planet, HD 209458b was found (Charbonneau *et al.*, 2000; Henry *et al.*, 2000). Transiting planets, uniquely, allow the planetary mass and radius to be determined, and enable a plethora of further characterisation observations to be performed. Although HD 209458b was discovered using the radial velocity technique, its transits were first observed using telescopes of modest aperture. Henry *et al.* (2000) used a 0.8-m telescope, whilst Charbonneau *et al.* (2000) used an even smaller, 0.1-m instrument. The discoveries since 2000 made by the numerous transit surveys are summarised in Tab. 1. The instruments used fall into three broad categories: ground-based, wide-field surveys, ground-based narrow-field surveys and space-based missions. The deep, narrow-field Optical Gravitational Lensing Experiment (OGLE; Udalski *et al.*, 2002) was responsible for the discovery of many

Table 1. Discoveries of transiting exoplanetary systems. Numbers are from `http://exoplanet.eu` (2013 September). G = ground, S = space, d = deep, w = wide.

Experiment	Type	No.	Reference
Optical Gravitational Lensing Experiment (OGLE)	G, d	8	Udalski *et al.* (2002)
Wide Angle Search for Planets (WASP)	G, w	109*	Pollacco *et al.* (2006)
Hungarian Automated Telescope Network (HATNet)	G, w	49	Bakos *et al.* (2002)
XO	G, w	5	McCullough *et al.* (2005)
Other ground-based surveys	G	17	See `http://exoplanet.eu`
Convection, Rotation and Transits (CoRoT)	S	23	Auvergne *et al.* 2009
Kepler	S	> 100**	Borucki *et al.* (2010)
Sagitarius Window Eclipsing Extrasolar Planet Search (SWEEPS)	S	2	Sahu *et al.* (2006)

*Of these 109, 70 are published.

**In addition to around 100 confirmed planets, *Kepler* has discovered several thousand planet candidates, the majority of which are probably planets.

of the first-known transiting planets, and the space missions CoRoT (Auvergne *et al.*, 2009) and *Kepler* (Borucki *et al.*, 2010) have made numerous discoveries more recently. The remainder of this paper, however, will focus on the significant contribution made by relatively inexpensive ground-based transit surveys, of which the Wide Angle Search for Planets (WASP) is the leading example.

2. SuperWASP: an overview

A full description of the WASP project is provided in Pollacco *et al.* (2006), but the project is summarised here. WASP is a consortium of United Kingdom universities who operate robotic telescope installations at the Issac Newton Group (ING) at the Observatorio del Roque de los Muchachos, La Palma, Spain and at the South African Astronomical Observatory (SAAO), Sutherland, RSA. The consortium works closely with colleagues at the Université de Genève, the Université de Liège and the Institut d'Astrophysique de Paris to follow-up and confirm discoveries.

2.1. Hardware

The hardware used at the two installations, SuperWASP-N (La Palma) and WASP-South (Sutherland), is essentially identical, although there are some relatively minor differences. We focus here on a description of the WASP-South installation. The instrument is housed in a shed-like fibreglass enclosure, divided into two rooms. The first room is covered by a hydraulically-operated slide-away roof and contains a mount which holds the cameras. The second room contains the several computers used in operating the telescope and storing the data, as well as acting as a store for supplies and spare parts. The mount is a single *Torus* fork mount, with a $30''$rms pointing error and a tracking error of less than $0.01\,''\,\mathrm{s}^{-1}$.

The mount holds eight *Canon* 200 mm f/1.8 lenses, each of 0.11 m aperture (this gives a total effective aperture of 0.31 m per installation). Each lens is backed by a 2048 x 2048 pixel *Andor* CCD, Peltier cooled to 223 K. The field-of-view of each camera is $7.8\,^{\circ}\,\mathrm{x}\,7.8\,^{\circ}$, which results in a plate scale of $13\,''\,\mathrm{pixel}^{-1}$, and means that all eight cameras between them can image around one per cent of the whole sky in a single exposure. The ambient temperature was discovered to affect the focus of the lenses, and hence the data quality and so modifications were introduced to keep the focus constant throughout the night. At SuperWASP-N, heated lens covers are used to maintain a constant lens temperature, while WASP-South uses an active focus feedback mechanism to control the focus throughout the night.

A dedicated weather station mounted on a mast outside the enclosure monitors cloud cover, moisture and wind speed and direction, and a satellite feed provides lightning and storm information. This data is used to determine whether the current conditions are suitable for observing, and enable the enclosure roof to be quickly closed (using emergency battery power if the mains power has failed) during bad weather. A 'live status' webpage[1] allows the monitoring of weather information, instrument status, the latest webcam images of the enclosure and mount, and thumbnails of the most recent science frames.

2.2. Observing strategy

The observing strategy employed by both instruments has typically been to observe around a dozen fields per night across a strip of constant declination, but the galactic plane is avoided for reasons of crowding. Two 30 s exposures are taken at each visit, and the typical cadence is around 10 minutes. Fields are followed for a full season of around five months, and the greatest coverage to date is of the region surrounding the celestial equator, which has been observed by both the northern and southern instruments (see Fig. 1).

2.3. Data processing

Since on a clear night, each camera may generate up to 1000 images, and each image occupies around 5 MB when compressed (8 MB uncompressed), there is around 40 GB of data to transfer for each full night's observation. There is sufficient bandwidth available at SuperWASP-N to transfer the raw data over

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[1] viewable at `http://wasp.astro.keele.ac.uk/live/`

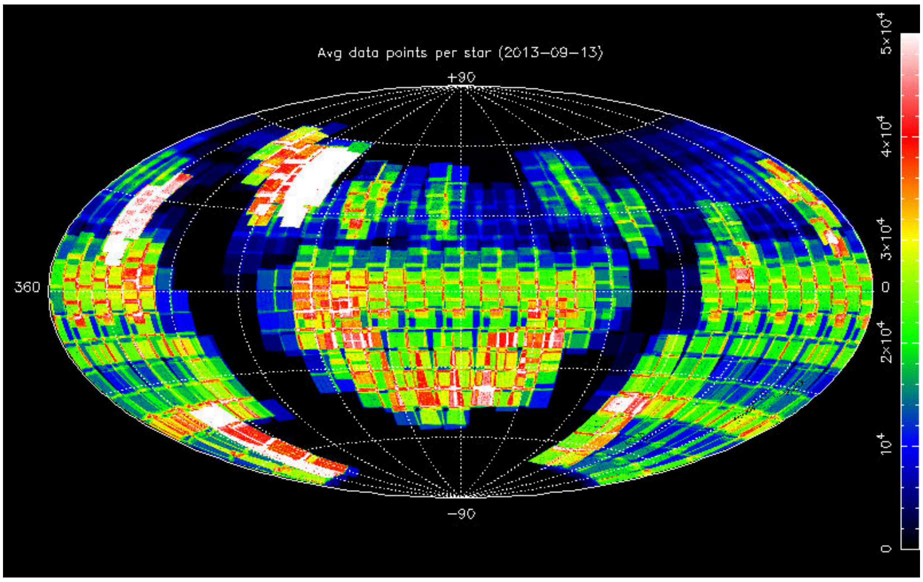

Figure 1. WASP coverage map. Average data points per star in the WASP archive (as of 2013 September), as a function of sky position (equatorial coordinates).

the internet, but at WASP-South hard disk drives have replaced data tapes as the means of data transfer; a 1 TB disk is returned to the UK every four to six weeks. Raw data are stored in the WASP archive at Warwick (formerly Leicester), which currently contains around 7.7×10^6 raw images, occupying some 60 TB.

After standard data calibration methods are applied, aperture photometry is performed on objects fainter than about $V = 9.5$ and brighter than $V = 13$ (see Pollacco *et al.*, 2006 for a description of the data reduction pipeline). The processed data is also stored in the archive, where there are 4.3×10^{11} data points on 3.1×10^7 unique objects (as at 2013 September).

2.4. Public data archive

The first WASP public data release described by Butters *et al.* (2010) is now hosted by NASA[2] and by Masaryk University, Brno[3]. This limited data release consists of 18 million publicly-downloadable light curves in the declination ranges $+20° < \delta < +66°$ (from SuperWASP-N) and $-90° < \delta < -20°$ (from WASP-South). The data span 2004 – 2008.

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[2] `http://exoplanetarchive.ipac.caltech.edu/docs/SuperWASPMission.html`

[3] `http://wasp.cerit-sc.cz/form`

2.5. Searching for transits

A more complete description of the planet-hunting process is given by Collier Cameron *et al.* (2006; 2007 b), but in brief: light curves are de-trended for correlated systematics (Smith *et al.* 2006) using the SysRem (Tamuz *et al.*, 2005), TFA (Kovács *et al.*, 2005) algorithms. Transit searching is performed using a box-least-squares algorithm. A webpage containing various graphs, parameters, including a phase-folded light curve, a periodogram, is generated for each potential planetary system. Fig. 2 shows a typical WASP phase-folded light curve for a transiting planetary system. Various metrics are used in the candidate filtering, but this process is not entirely automated; candidates must be individually inspected by a human. Candidates may be rejected as either 'junk', where the 'transits' are caused by noise, or as astrophysical false-positives (transits are obviously not caused by a planetary body). Alternatively candidates may be sent for follow-up observations (spectra or photometry) or saved for the arrival of future WASP data to determine their fate.

2.6. Planet confirmation

Follow-up observations with larger telescopes are required to confirm the planetary nature of our targets: radial velocities are require to confirm that the companion object is of planetary mass, and more precise transit photometry allows the determination of the system parameters with greater precision. A single spectrum is sufficient to rule out some candidates, e.g. giants, fast rotators, etc, while transit photometry using a telescope / instrument combination with a finer plate scale than WASP is particularly important when the candidate object has nearby neighbours, so we can be sure which star exhibits transits.

Photometric follow-up is performed using a range of telescopes, most commonly the 0.6-m robotic TRAPPIST telescope (Jehin *et al.*, 2011), the 1.2-m Swiss Euler telescope (both at La Silla), the 2-m robotic Liverpool telescope on La Palma, the 2-m Faulkes Telescopes North and South, on Maui and at Siding Springs respectively. The telescopes of several UK universities are also often used, particularly for candidate filtering, including the 1-m James Gregory Telescope in St. Andrews, and the 0.6-m telescope at Keele.

Precision radial velocities are obtained from several instruments, including CORALIE on the Swiss Euler, HARPS on the ESO 3.6-m at La Silla, and SOPHIE on the 1.93-m at Haute-Provence. Most candidates are found to be low-mass / grazing / diluted eclipsing binary systems, although around 1 in 12 candidates is confirmed as a planet. This 'hit rate' is somewhat lower than it could be, due to the practice of sending 'high risk, high reward' systems for follow-up, such as marginal transit detections that would result in particularly small planets for example.

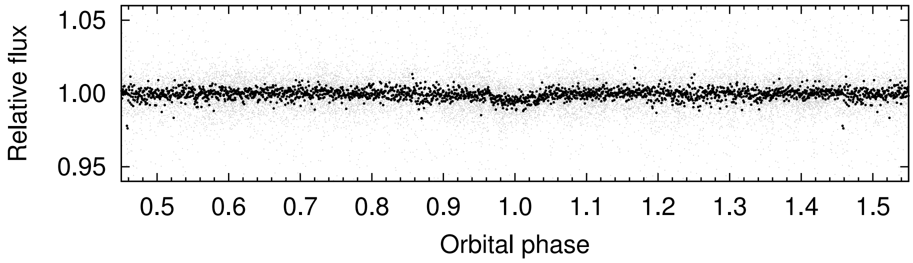

Figure 2. Typical WASP transit light curve – WASP-71 (Smith *et al.*, 2013) as observed by SuperWASP-N and WASP-South, folded on the orbital period of 2.9 d. Unbinned points are grey, and points binned in phase (with an equivalent bin width of 120 s) are black.

3. Scientific highlights from the WASP instruments

Here, we briefly highlight just some of the science enabled by WASP observations, over the last few years.

3.1. Exoplanet discoveries

Since the discovery of WASP's first planets (Collier Cameron *et al.*, 2007 a), when only twelve transiting planets were known, a total of 109 transiting planetary systems (of around 300 known) have been discovered by WASP, of which 70 have been published (Table 1). The remainder are awaiting further data, or have discovery papers in preparation. Of the 70 published WASP discoveries, the host stars have V magnitudes in the range 8.3 – 13.0 (median: 11.6), orbital periods in the range 0.8 – 8.2 d (3.1 d), masses in the range 0.24 – 10.4 times that of Jupiter (0.9) and radii in the range 0.78 – 2.0 times that of Jupiter (1.2). Three of the more exceptional exoplanetary systems discovered by WASP are briefly introduced below.

3.1.1. WASP-12b

The relatively bright host star, large, close-orbiting planet make WASP-12 (Hebb *et al.*, 2009) one of the most amenable systems to follow-up observations to probe the planet's atmosphere. Observations of the occultation (secondary eclipse) from the ground (Croll *et al.*, 2011), from *Spitzer* (Campo *et al.*, 2011) cannot be explained by conventional, solar-composition, atmospheric models; only by an exotic carbon-rich atmosphere (Madhusudhan *et al.*, 2011). WASP-12b remains an object of intense interest for atmospheric characterisation observations, with recent results indicating that aerosols may play a key role in the atmosphere (Sing *et al.*, 2013).

3.1.2. WASP-17b

Measurements of the Rossiter-McLaughlin effect revealed WASP-17b to be the first known planet to orbit its star in the opposite (retrograde) direction to the stellar rotation (Anderson *et al.*, 2010; Triaud *et al.*, 2010). Such planets play a vital role in understanding the formation, evolution of hot Jupiters, specifically the role played by migration, tidal interaction. The planet is also the largest known, with a radius 2.0 times that of Jupiter, as confirmed by the occultation measurements of Anderson *et al.* (2011 a), which removed a degeneracy between orbital eccentricity, planetary radius. Large radii such as these were unpredicted and are as yet unexplained, continuing to pose questions for models of planet formation.

3.1.3. WASP-33b

WASP-33b was the first planet to be discovered orbiting an A-type star, and the first to be confirmed using line-profile tomography instead of the more usual radial velocity method (Collier Cameron *et al.*, 2010). The star is a δ-Scuti-like pulsator (also a first) and the planet's orbit ($P = 1.2\,\mathrm{d}$) is retrograde with respect to the stellar spin axis. Observations of the occultation confirmed the planet as the hottest yet discovered (Smith *et al.*, 2011).

3.2. Other science

Exoplanet science is not the only field which benefits from wide-angle surveys such as WASP. WASP data had been used to study various astrophysical objects, including:

3.2.1. Low-mass stellar and sub-stellar objects

The brown dwarf WASP-30b (Anderson *et al.*, 2011 b) is one of just a handful known to transit. This makes it an extremely valuable object for understanding the mass – radius relation at masses intermediate to those of planets and main-sequence stars. WASP has also discovered low-mass eclipsing binaries (EBLMs) with masses greater than those of brown dwarfs (Triaud *et al.*, 2013).

3.2.2. Solar System objects

WASP data has also been used to study objects in our Solar System, including the rotation of asteroids (Parley *et al.*, 2005) and the outburst of Comet 17P/Holmes (Hsieh *et al.*, 2010).

3.2.3. Star clusters

WASP light curves were used to study stellar rotation in the Hyades and in Praesepe by Delorme *et al.* (2011), and to derive a colour – rotation relation for the stars in Coma Berenices by Collier Cameron *et al.* (2009).

3.2.4. Variable stars and EBs

All manner of variable stars and eclipsing binaries (EBs) have been studied using WASP photometry, including short-period EBs (Norton *et al.*, 2011; Lohr *et al.*, 2012; 2013), variable stars coincident with known X-ray sources (Norton *et al.*, 2007), cataclysmic variables on long time-scales (Thomas *et al.*, 2010), pulsations in Am stars (Smalley *et al.*, 2011), and oscillations in roAp stars (Elkin *et al.*, 2011).

4. The future of ground-based surveys

Kepler has discovered more than 100 transiting planets, and many thousands of planetary candidates, with an estimated global false positive rate of just 9.4 per cent (Fressin *et al.*, 2013). These discoveries include many planets that are smaller and have longer periods than any transiting planets discovered from the ground. However, *Kepler* has only observed one relatively small field, and most of the targets are relatively faint ($V \approx 15$).

It is for these two reasons that ground-based transit surveys still have a future role to play. Wide-field transit surveys cover a large area of sky and hence find intrinsically rare objects, such as the hugely bloated WASP-17b (Sec. 3.1.2). Furthermore, future exoplanet characterisation efforts, including future space-based missions such as CHEOPS (Broeg *et al.*, these proceedings), require targets that (i) orbit bright stars and (ii) are distributed across the sky, e.g. southern objects for the E-ELT to observe.

4.1. The SuperWASP instruments

WASP is still finding new planets, and is likely to continue to do so for some time. At present, SuperWASP-N is trialling a different observing strategy, where fewer fields are observed but with higher cadence, with the goal of finding smaller planets. WASP-South, meanwhile, is operating with new, wider angle lenses in order to find planets orbiting brighter stars. These 85 mm, f/1.2 lenses have the effect of increasing the field-of-view to $18^\circ \times 18^\circ$ and changing the faint magnitude limit from about 9.5 to about 7.0 (V). The motivation for this is that no southern analogue to the brightest-known transiting planetary systems, HD209458 and HD189733 is known, and such an object would be an extremely valuable target for characterisation observations, as the brightest northern systems have proved.

4.2. Related surveys

Two wide-field transit surveys exist that build on the legacy (hardware, software, expertise) of the WASP project. They are:

4.2.1. The Qatar Exoplanet Survey (QES)

QES currently operates four 400 mm lenses ($5^\circ \times 5^\circ$ field-of-view) in New Mexico, and funding has been secured from the Qatar National Research Fund for additional stations. The goal is to be able to discover planets around one magnitude fainter than WASP; two planets have been discovered to date, Qatar-1b (Alsubai *et al.*, 2011) and Qatar-2b (Bryan *et al.*, 2012).

4.2.2. The Next Generation Transit Survey (NGTS)

NGTS[4] (Wheatley *et al.*, 2013) will operate a total of twelve independently-mounted 0.2-m telescopes to survey the sky from Paranal, Chile. The survey is designed to target bright ($V < 13$) stars, and to discover planets of Neptune-size and smaller. Sensitivity to late-type host stars (K and early-M-type) is achieved by operating in the $600 - 900$ nm band, enabling the detection of smaller planets.

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[4] `http://www.ngtransits.org`

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