Publications of the Astronomical Society of the Pacific, **118**: 1245–1248, 2006 September

SuperWASP Observations of the Transiting Extrasolar Planet XO-1b

D. M. Wilson,[1] B. Enoch,[2] D. J. Christian,[3] W. I. Clarkson,[2,4] A. Collier Cameron,[5] H. J. Deeg,[6] A. Evans,[1] C. A. Haswell,[2] C. Hellier,[1] S. T. Hodgkin,[7] K. Horne,[5] J. Irwin,[7] S. R. Kane,[5,8] T. A. Lister,[1,5] P. F. L. Maxted,[1] A. J. Norton,[2] D. Pollacco,[3] I. Skillen,[9] R. A. Street,[3] R. G. West,[10] and P. J. Wheatley[11]
Received 2006 June 26; accepted 2006 July 26; published 2006 August 24

ABSTRACT. We report on observations of 11 transit events of the transiting extrasolar planet XO-1b by the SuperWASP North observatory. From our data, obtained during 2004 May–September, we find that the XO-1b orbital period is 3.941634 ± 0.000137 days, the planetary radius is $1.34R_J \pm 0.12R_J$, and the inclination is 88°.92 ± 1°.04, in good agreement with previously published values. We tabulate the transit timings from 2004 SuperWASP and XO data, which are the earliest obtained for XO-1b and which will therefore be useful for future investigations of timing variations caused by additional perturbing planets. We also present an ephemeris for the transits.

1. INTRODUCTION

Although the current list of confirmed exoplanets stands at over 180,[12] only 10 have been found to transit their parent star. Transiting planets allow the true planetary mass, radius, density, and inclination to be determined, allowing us to place constraints on fundamental theories of planet formation and evolution. The SuperWASP project is one of a number of wide-angle searches for extrasolar planetary transits. In this paper, we demonstrate the capabilities of the SuperWASP cameras and transit-searching algorithm by reporting observations of 11 transits of an 11th magnitude star by the exoplanet XO-1b (McCullough et al. 2006), observed during the first season of SuperWASP observations in 2004.

2. SuperWASP OBSERVATIONS

The SuperWASP (Wide Angle Search for Planets) project[13] is an automated ultra–wide-angle photometric survey covering both northern and southern hemispheres. SuperWASP North (SW-N) is based on La Palma, Canary Islands, and SuperWASP South (SW-S) is based at the South African Astronomical Observatory (SAAO). Both observatories consist of eight cameras, each with an 11.1 cm aperture, 200 mm Canon f/1.8 lens backed by a 2K × 2K EEV CCD. Each camera has a field of view of 7°.8 × 7°.8 with a 13″.7 pixel^{-1} plate scale, resulting in a total field of view of almost 500 deg^2 per observatory. Further details of the project are given in Pollacco et al. (2006).

The SW-N observatory obtained nearly 4500 individual observations of XO-1 over 150 days between 2004 May 2 to September 29. The object was recorded by two cameras, producing a total of 8875 measurements. The photometric precision, when outliers from cloudy nights are excluded, is approximately 9 mmag (rms). This is slightly worse than usual for stars of this magnitude, owing to the close proximity to the edges of the camera fields.

Light curves from SuperWASP are detrended using the algorithm given in Tamuz et al. (2005) before being passed through HUNTER (Collier Cameron et al. 2006), a transit-search algorithm based on the method given in Protopapas et al. (2005). The algorithm computes χ^2 values of transit model light curves using a box-shaped model that is slid over the observed light curve. Typically, a few tens of transit-like light curves are identified from each CCD field of 10,000–20,000 objects.

The HUNTER output for XO-1 (1SWASP J160211.83 +281010.4) is shown in Figure 1. The periodogram shows the value of χ^2 for the best least-squares fit at each frequency; the

[1] Astrophysics Group, School of Chemistry and Physics, Keele University, Staffordshire ST5 5BG, UK.

[2] Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK.

[3] Astrophysics Research Centre, Main Physics Building, School of Mathematics and Physics, Queen's University, University Road, Belfast BT7 1NN, UK.

[4] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

[5] School of Physics and Astronomy, University of Saint Andrews, North Haugh, Saint Andrews, Fife KY16 9SS, UK.

[6] Instituto de Astrofísica de Canarias, Calle Via Láctea s/n, E-38200 La Laguna, Tenerife, Spain.

[7] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK.

[8] Department of Astronomy, University of Florida, 211 Bryant Space Science Center, Gainesville, FL 32611-2055.

[9] Isaac Newton Group of Telescopes, Apartado de Correos 321, E-38700 Santa Cruz de la Palma, Tenerife, Spain.

[10] Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK.

[11] Department of Physics, University of Warwick, Coventry CV4 7AL, UK.

[12] See http://exoplanet.eu.

[13] See http://www.superwasp.org.

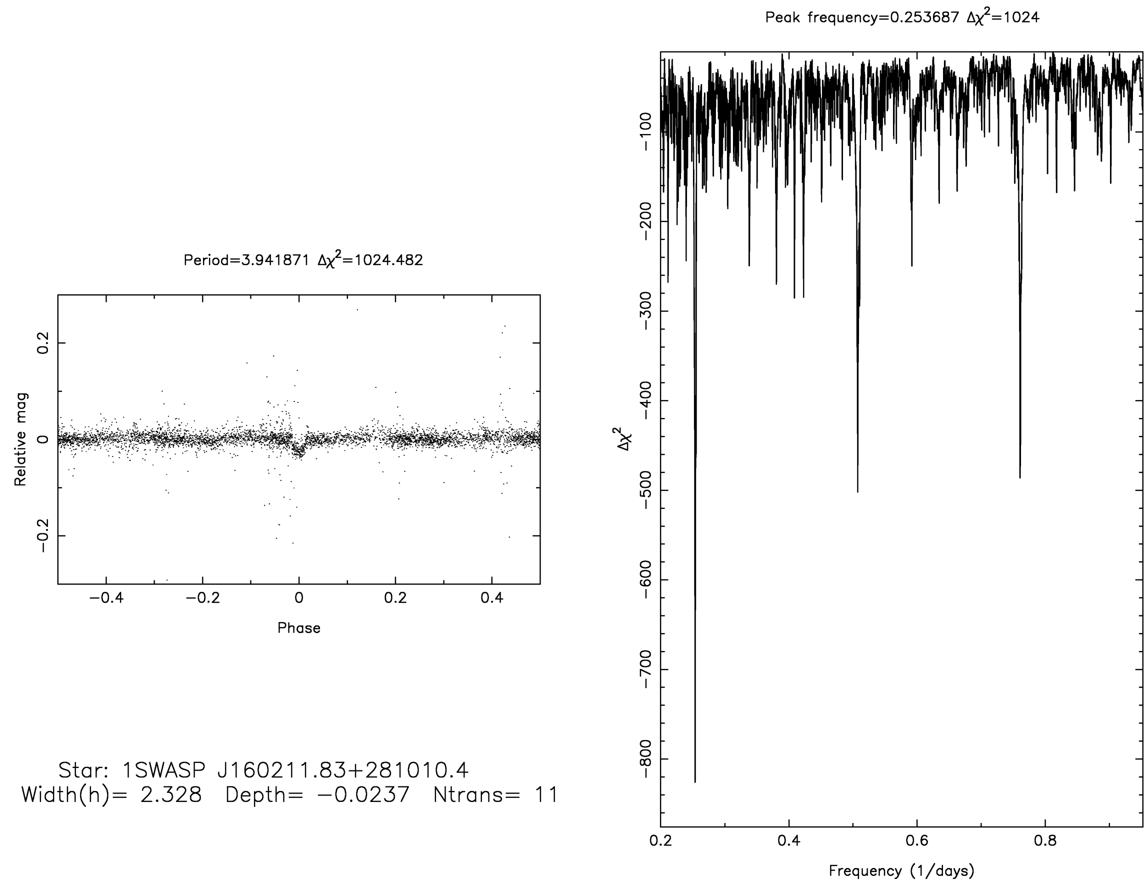

FIG. 1.—HUNTER output for object 1SWASP J160211.83+281010.4 (camera 2), including periodogram and light curve folded on the HUNTER-determined best-fitting period of 3.942134 days.

detrended light curve is phase-folded on the best-fitting period of 3.942134 days. HUNTER listed this object as a high-priority candidate to be considered for further investigation.

3. LIGHT-CURVE FITTING

The SW-N data cover 11 transit events and, excluding outliers, consist of 8468 data points. The transits were fitted to a simulated planetary transit generated using EBOP (Eclipsing Binary Orbit Program; Popper & Etzel 1981). EBOP uses biaxial ellipsoids to simulate eclipsing binary star systems; however, by considering the secondary as an opaque disk, a transiting planetary system can easily be modeled. The simulated light curve is dependent on the radii ratio of the transiting planet to the parent star, $R_{pl}/R_\star$, the inclination of the transiting planet's orbit, i_p, and the limb-darkening coefficient of the star.

TABLE 1
BEST-FITTING PARAMETERS OF XO-1 FROM THE FIT OF THE SW-N DATA

Parameter	SW-N
Period (days)	3.941634 ± 0.000137
T_0 (HJD)	2,453,150.6849 ± 0.0018
$R_{pl}/R_\star$	0.138 ± 0.020
i_p (deg)	88.92 ± 1.04
$R_\star$ ($R_\odot$)	1.0 ± 0.08[a]
R_{pl} (R_J)	1.34 ± 0.12

[a] From McCullough et al. (2006).

The limb-darkening coefficient was determined by convolving the SuperWASP bandpass with fluxes and monochromatic coefficients listed by Van Hamme (1993). A linear limb-darkening coefficient of 0.565 was calculated for the stellar temperature of 5750 K (G1 V), quoted by McCullough et al. (2006).

The best-fit parameters determined from a least-squares fit to all transits simultaneously are listed in Table 1. Figure 2 shows the data phase-folded on the best-fitting period, with the best-fit model overplotted. The original XO survey data (P. McCullough 2006, private communication), obtained on an instrument similar to SW-N, are also shown for comparison. The errors were generated using a bootstrap Monte Carlo method in which we generated and refitted 1000 simulated data sets from the best-fit light curve with the same sampling and noise characteristics as the observed light curve. The planetary radius was determined from the ratio $R_{pl}/R_\star$ by using the stellar

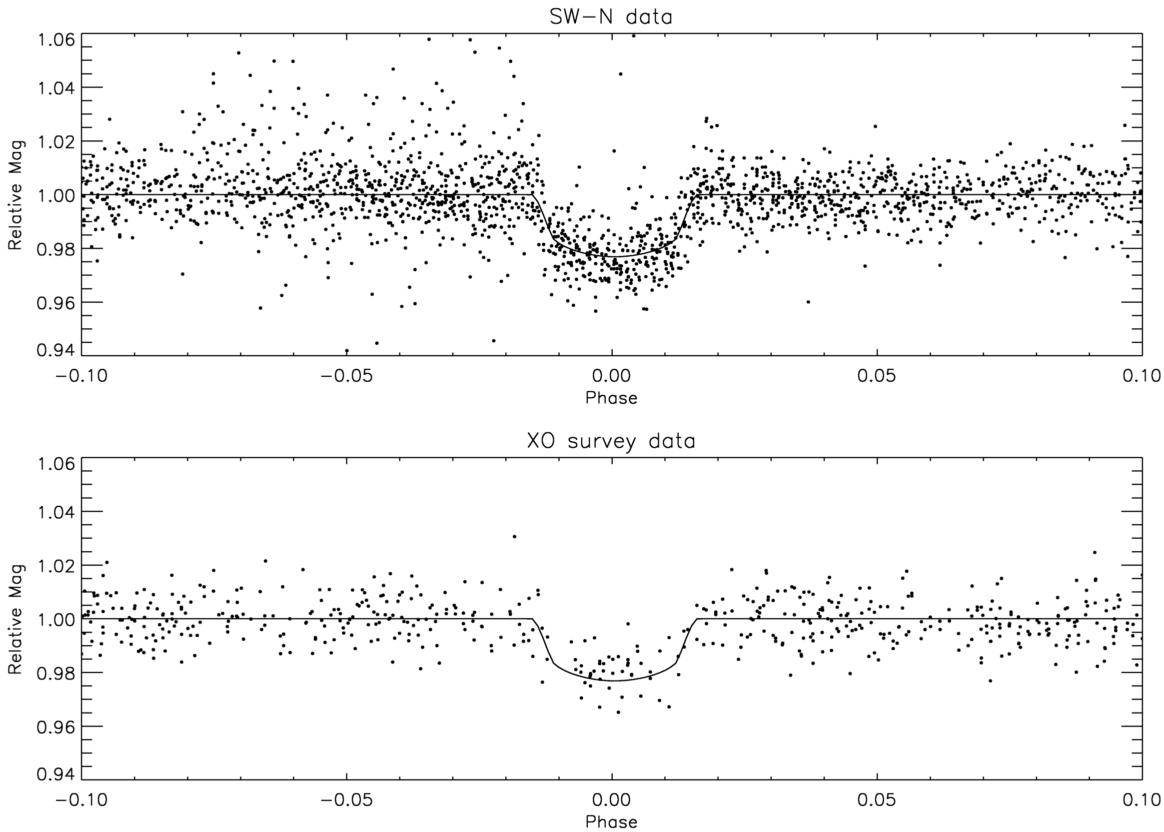

FIG. 2.—SuperWASP North data (*top*) and XO survey data (*bottom*) for XO-1 phase folded on the best-fitting parameters listed in Table 1, with the best-fit model overplotted.

TABLE 2

BEST-FIT TIMES OF MIDTRANSIT FOR FULL AND PARTIAL XO-1b TRANSITS FROM SW-N AND XO SURVEY DATA

Observatory	HJD (Midtransit)	Transit	Points[a]
XO	2,453,123	No fit[b]	
	2,453,127.0385 ± 0.0058	Partial	32
	2,453,142.7818 ± 0.0218	Partial	40
SW-N	2,453,146	No fit[b]	
	2,453,150.6855 ± 0.0106	Partial	88
	2,453,154.6250 ± 0.0026	Full	99
	2,453,158.5663 ± 0.0034	Full	102
	2,453,162.5137 ± 0.0025	Full	117
	2,453,166.4505 ± 0.0025	Partial	68
	2,453,170.3917 ± 0.0037	Partial	65
	2,453,229.5143 ± 0.0045	Partial	54
	2,453,233	No fit[b]	
	2,453,237.4043 ± 0.0032	Partial	47
	2,453,241.3410 ± 0.0067	Partial	38

[a] Number of data points covering the transit; i.e., within the phases 0.96–1.04.

[b] The data for HJD 2,453,123 and HJD 2,453,233 cover less than half of the transit and so were rejected. The data for HJD 2,453,146 are too noisy to provide a reliable transit time measurement.

radius of 1.0 ± 0.08 $R_\odot$ determined spectroscopically by McCullough et al. (2006). The parameters determined from the fit are consistent with previously published values (McCullough et al. 2006).

Eleven transit events were identified from the determined period and ephemeris, and the best-fit model was fitted to each of these individually in order to determine the time of midtransit, T_0 (Table 2). The best-fit model was also fitted to the XO survey data, which were also obtained in 2004 and cover three transit events. Three of the total 14 transits were rejected, either due to insufficient coverage of the transit event or, in one case, because the data were too noisy to produce an adequate fit. The errors were generated by perturbing T_0 so as to increase χ^2 by 1, and are typically on the order of 5–10 minutes, which is comparable to the data sampling rate.

This paper has demonstrated that SuperWASP can detect and characterize exoplanet transits and obtain sufficient data to determine an ephemeris. Other candidate exoplanet transits from our 2004 data will be reported in subsequent papers.

The WASP consortium consists of representatives from the Universities of Cambridge (Wide Field Astronomy Unit), Keele, and Leicester, The Open University, Queen's University Belfast, and Saint Andrews, along with the Isaac Newton Group (La Palma) and the Instituto de Astrofísica de Canarias (Tenerife). The SuperWASP-N and SuperWASP-S cameras were constructed and operated with funds made available from consortium universities and PPARC.

We are grateful to the XO team for making available the original XO photometry.

REFERENCES

Collier Cameron, A., et al. 2006, MNRAS, submitted
McCullough, P. R., et al. 2006, ApJ, in press
Pollacco, D., et al. 2006, PASP, submitted
Popper, D. M., & Etzel, P. B. 1981, AJ, 86, 102
Protopapas, P., Jimenez, R., & Alcock, C. 2005, MNRAS, 362, 460
Tamuz, O., Mazeh, T., & Zucker, S. 2005, MNRAS, 356, 1466
Van Hamme, W. 1993, AJ, 106, 2096