

A new detached K7 dwarf eclipsing binary system

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ABSTRACT

We present an analysis of a new, detached, double-lined eclipsing binary system with K7 Ve components, discovered as part of the University of New South Wales (UNSW) Extrasolar Planet Search. The object is significant in that only six other binary systems are known with comparable or lower mass. Such systems offer important tests of mass–radius theoretical models. Follow-up photometry and spectroscopy were obtained with the 40-inch and 2.3-m telescopes at Siding Spring Observatory (SSO), respectively. An estimate of the radial velocity amplitude from spectral absorption features, combined with the orbital inclination (83.5°) estimated from light-curve fitting, yielded a total mass of $M_{\text{total}} = 1.041 \pm 0.06 M_\odot$ and component masses of $M_A = 0.529 \pm 0.035 M_\odot$ and $M_B = 0.512 \pm 0.035 M_\odot$. The radial velocity amplitude estimated from absorption features ($167 \pm 3 \text{ km s}^{-1}$) was found to be less than the estimate from the H α emission lines ($175 \pm 1.5 \text{ km s}^{-1}$). The light-curve fit produced radii of $R_A = 0.641 \pm 0.05 R_\odot$ and $R_B = 0.608 \pm 0.06 R_\odot$, and a temperature ratio of $T_B/T_A = 0.980 \pm 0.015$. The apparent magnitude of the binary was estimated to be $V = 13.9 \pm 0.2$. Combined with the spectral type, this gave the distance to the binary as $169 \pm 14 \text{ pc}$. The timing of the secondary eclipse gave a lower limit on the eccentricity of the binary system of $e \geq 0.0025 \pm 0.0005$. This is the most statistically significant non-zero eccentricity found for such a system, possibly suggesting the presence of a third companion.

Key words: binaries: eclipsing – binaries: spectroscopic – stars: individual: UNSW-TR-2 – stars: late-type – stars: low-mass.

1 INTRODUCTION

Low-mass stars ($M < M_\odot$) make up more than 70 per cent of the stellar population, but their intrinsic faintness means that relatively few have been studied in detail. In recent years, much work has been done on the theoretical modelling of such stars (see review by Chabrier & Baraffe 2000), but progress has been hindered by a lack of observed low-mass stars with sufficiently accurate parameters. In order to distinguish between the various models, uncertainties of less than 2–3 per cent in the masses and radii are required (Ribas 2003, 2005). This can most easily be achieved with detached, double-lined eclipsing binary stars, with best results coming from systems with similar components (Ribas 2005). Currently, only six such systems with masses of $0.6 M_\odot$ or below are known. A number of recent studies of these systems (Torres & Ribas 2002; Ribas 2003; Maceroni & Montalbán 2004; López-Morales & Ribas 2005) have revealed discrepancies between the observations and the latest theoretical models, which in particular appear to underestimate

the radii by as much as 10–15 per cent. This is possibly due to the enhanced magnetic activity produced by the high rotational velocities of stars in close binaries (Ribas 2005). There is a clear need for more of these systems to be discovered and studied, so that the physics of low-mass stars may finally be understood.

In this paper, we report the discovery and preliminary analysis of a new detached, double-lined eclipsing binary system with K7 Ve components. The system was detected in data obtained for the University of New South Wales (UNSW) Extrasolar Planet Search (Hidas et al. 2005). The eclipses are grazing, and their depths were diluted by light from a brighter, blended star. The resulting shallow eclipses led to this object's selection as a transiting planet candidate, its true nature only being revealed by follow-up observations.

2 OBSERVATIONS

2.1 Photometry

The data leading to the detection of UNSW-TR-2 ($\alpha_{J2000} = 18^{\text{h}} 30^{\text{m}} 52^{\text{s}}.3$; $\delta_{J2000} = +7^\circ 9' 27''$) were obtained using the 0.5-m Automated Patrol Telescope (APT) at Siding Spring Observatory

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(SSO), NSW, Australia. The object was found in a field centred on the open cluster NGC 6633. During three seasons (2002–2004) we observed this field on 79 nights (about 3500 images). For most of the present analysis, we have used only the best quality data (highest cadence and lowest photometric noise), consisting of 997 images from 11 nights in 2002 July and August. On these nights we observed through a Johnson *V* filter at a cadence of about 16 h^{-1} . The remaining data on this field have one quarter the cadence (we were observing three other fields in parallel) and are affected by significant systematic trends on many nights. For the period determination (Section 3.1), we used the entire data set. Light curves were extracted using a custom-built automated reduction pipeline. For more information about the telescope, the data and the reduction process, see Hidas et al. (2005).

Initial inspection of the light curve of UNSW-TR-2 revealed eclipses with a depth of $\sim 25 \text{ m mag}$, a duration of 2 h, and a binary period of $\sim 2.1 \text{ d}$. The out-of-eclipse magnitude is $V = 12.0 \pm 0.1$, but inspection of a Digitized Sky Survey (DSS)¹ image revealed that the APT photometry aperture contains at least two blended stars of similar brightness. The APT has 9.4-arcsec pixels, and in a crowded field such as this one (at galactic latitude $+8^\circ$), such blending is common. The photometry aperture is 3 pixels in radius.

In 2004 June, we obtained images of UNSW-TR-2 at higher spatial resolution in *V* and *I* using the 40-inch telescope at SSO. The images were sampled by 0.6 arcsec pixels. We observed one complete eclipse (in ~ 3 -arcsec seeing), with a depth of 0.14 mag. The eclipse has the same depth and shape (within the photometric errors) in the two colour bands, suggesting that the two stars are of similar temperature.

The binary system is in fact the second brightest object in the APT photometry aperture. It is $1.48 \pm 0.03 \text{ mag}$ fainter than the brightest one, and separated from it by $\sim 10 \text{ arcsec}$. The Tycho-2 catalogue (Høg et al. 2000) gives a (Johnson) *V* magnitude of 12.4 ± 0.2 for this bright neighbour. The combined apparent magnitude for the binary system is therefore $V = 13.9 \pm 0.2$. Infrared magnitudes of the binary and its neighbour (from the 2-micron All-Sky Survey) are shown in Table 1.

2.2 Spectroscopy

2.2.1 Spectra obtained

Spectra were obtained using the Double-Beam Spectrograph (DBS) on the 2.3-m telescope at SSO. During our initial follow-up run in 2004 June, we obtained two spectra of UNSW-TR-2 at the same epoch (Fig. 1). These covered the range 5800–6600 Å with 60 km s^{-1} resolution [full width at half-maximum (FWHM), as measured from the sky lines in the spectra].

Visual comparison of the flux-calibrated spectra with templates from the UVILIB spectral library (Pickles 1998) suggested that both stars are of type K7 V. With additional spectra reaching further into the red, our estimate of the spectral type could be refined using the TiO absorption bands (e.g. Kenyon & Fernandez-Castro 1987; Schild, Boyle & Schmid 1992). One TiO band is present in our existing data, but the absorption is very weak.

All of the absorption lines have two components, the smaller of which has 60–80 per cent of the depth of the larger component,

¹ The DSS was produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166, based on photographic data obtained using the Oschin Schmidt and UK Schmidt telescopes.

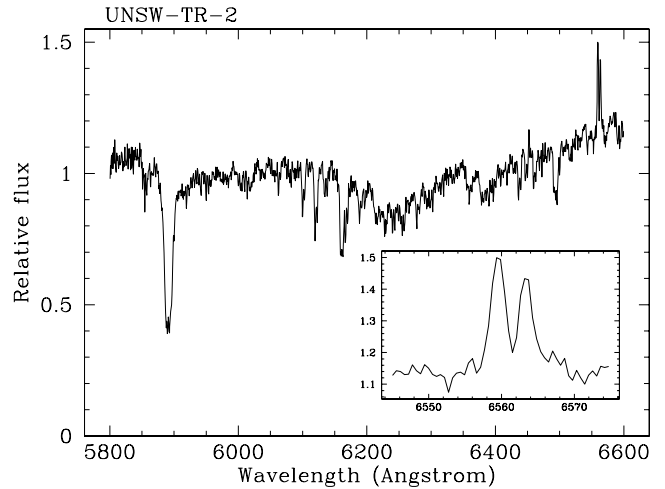


Figure 1. The spectrum of UNSW-TR-2, obtained at phase 0.213 using the 2.3-m telescope at SSO. The inset shows a close up of the $H\alpha$ lines.

pointing to two similar stars. Prominent $H\alpha$ emission is also present, with the two components at a similar strength ratio to the absorption-line pairs (Fig. 1).

The expected absolute magnitude of the two stars combined, based on their spectral type (K7 V), is $M_V = 7.6$ (Cox 2000). Combining this with our estimate of the system’s apparent magnitude ($V = 13.9 \pm 0.2$), and assuming 1 mag kpc^{-1} of extinction, puts the binary at a distance of $169 \pm 14 \text{ pc}$. The template best matching the spectrum of the bright neighbouring star is that of a G8III giant, with $M_V = 0.8$. Assuming the same extinction gives a distance of $1200 \pm 70 \text{ pc}$. Therefore, this neighbour is not physically associated with the binary system.

2.2.2 Radial velocity estimation

We fitted for the two stellar components simultaneously using vPFIT.² For both spectra, five absorption-line pairs with high signal-to-noise were individually fitted with blended Voigt profiles. When given the instrumental resolution, vPFIT fits for the central velocity, column density and Doppler broadening of each line and returns associated uncertainties based on the covariance matrix at the best fit. Each absorption-line pair is surrounded in our spectra by weak absorption features, some of which are partially blended with the pair in question. To allow for this, we inserted extra absorption lines into vPFIT as appropriate, again allowing all line parameters to vary. We found that in order to obtain reasonable fits it was also necessary to allow for the presence of a final weak subsidiary line internal to the main absorption-line pair. In all cases, this procedure produced a reasonable fit to the data ($\chi^2 \sim 1$).

A small adaptation of vPFIT allows for the fitting of emission lines with blended Gaussian profiles. In this way we fitted the two $H\alpha$ emission-line pairs. No subsidiary lines were required to obtain a good fit.

Taking orbital phase into account, and assuming a circular orbit, the total velocity amplitude $(K_A + K_B) \sin i$ is $167 \pm 3 \text{ km s}^{-1}$ when measured from the absorption features, and $175 \pm 1.5 \text{ km s}^{-1}$ when measured from the $H\alpha$ emission lines, where i is the orbital inclination of the system (subsequently determined by light-curve

² <http://www.ast.cam.ac.uk/~rfc/vpfit.html>

fitting, as described in Section 3.2). An apparent disagreement between velocities derived by these two methods has been noted in other systems (M. López-Morales, private communication). The absorption velocity is considered to be more reliable due to uncertainties as to the spatial distribution of the source of H α emission relative to the photometric centre of each star. We therefore adopt the value of $(K_A + K_B) \sin i = 167 \pm 3 \text{ km s}^{-1}$ for the velocity amplitude of our system. We were unable to improve upon this estimate using the two-dimensional cross-correlation software TODCOR (Mazeh & Zucker 1994) with a variety of different template spectra. This is possibly due to the relatively low resolution of our spectra when compared to those of similar objects for which TODCOR has been successfully implemented (e.g. López-Morales & Ribas 2005).

In 2006 March, we obtained an additional spectrum with the same instrument and at the same resolution. This one was taken close to an eclipse, therefore, the lines are completely blended and the separation of the absorption lines cannot be reliably measured. However, comparing the central wavelength of each blended line with the wavelengths of the separated components in the original spectra allows us to constrain the difference between the two masses. This was done for the five high signal-to-noise absorption lines in both of the original spectra, leading to a constraint of $\Delta M = M_A - M_B = (0.016 \pm 0.03)M_{\text{total}}$.

3 ANALYSIS

3.1 Period and eccentricity

Phase folding the entire APT light curve (with observed eclipses up to two years apart) allows a precise determination of the orbital period. The period giving the smallest scatter in the folded light curve is $2.11674 \pm 0.00002 \text{ d}$.

The epoch of the primary eclipse minimum (t_0) was determined from the 40-inch light curve. The secondary eclipse occurs at a phase of 0.5016 ± 0.0003 (measured from the APT light curve), $5 \pm 1 \text{ min}$ later than expected for a perfectly circular orbit. Assuming

that the major axis of the orbit lies in the plane of the sky gives a lower limit on the orbit's eccentricity of $e \geq 0.0025 \pm 0.0005$. Zahn & Bouchet (1989) predict that a binary consisting of two $0.5 M_{\odot}$ stars with a period of about 7 d and an initial eccentricity of 0.3 will have been circularized by tidal interactions to $e \simeq 0.005$ by an age of 10^6 yr , and will have reached $e \simeq 0.004$ after 10^{10} yr . However, the shorter period of our system should lead to increased circularization and lower e . Although our lower limit may be compatible with a simple, main-sequence binary system, it suggests the possibility that our system either is very young, or more likely, has at least one other companion affecting the timing of the eclipses. This is the most significant evidence for non-zero eccentricity in a low-mass eclipsing binary system detected to date. However, we continue to assume $e = 0$ for this work.

3.2 Light-curve fitting

We fitted models (based on equations by Sackett 1999, modified to apply to binary stars) to the light curves using a chi-squared minimization algorithm to estimate properties of the system. The APT light curve was folded and binned at 5-min intervals. All the data (one high-resolution primary eclipse in each of V and I bands from the 40-inch, and both eclipses in V from the APT) were fitted simultaneously. The accuracy of our results is limited by the lack of high spatial-resolution observations of the secondary eclipse, and also by the presence of the nearby brighter star in the APT aperture. The epochs of the primary and secondary minima, the period and the velocity amplitude were fixed at their previously measured values whilst allowing the orbital inclination (i), the radii of both stars (R_A and R_B), and their temperature ratio (T_B/T_A) to vary. Also required is the fraction F of the total flux in the APT aperture produced by our object, estimated as 0.19 ± 0.02 from the 40-inch images and allowed to vary within this error range. Finally, we assume solar-metallicity limb-darkening coefficients of 0.9 and 0.7 in V and I , respectively (Claret 1998). The best-fitting light curve is shown in Fig. 2, and the parameters are summarized in Table 2.

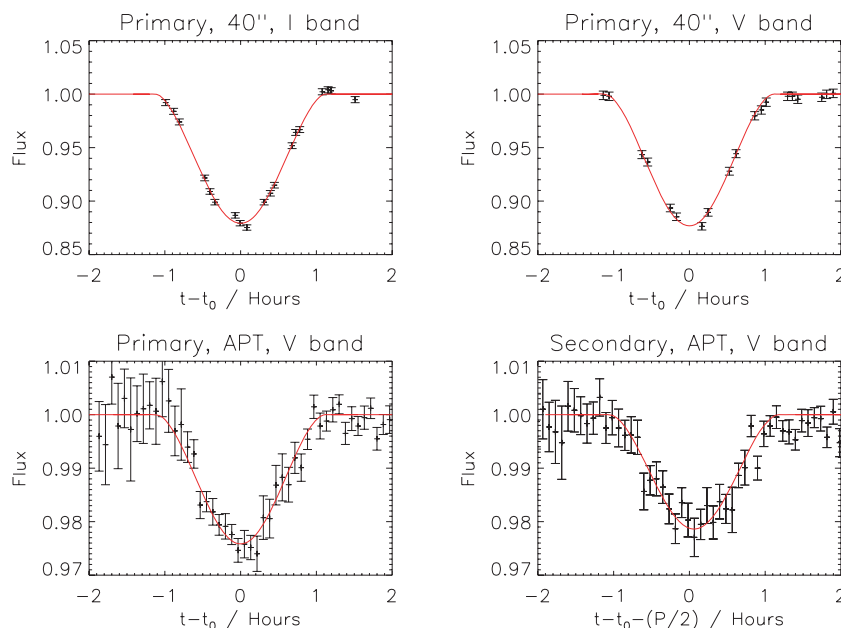


Figure 2. The four eclipses used in the parameter estimation. Top: the primary eclipse observed in both V and I with the Australian National University (ANU) 40-inch telescope. Bottom: both eclipses from the APT light curve, phase folded and binned at 5-min intervals. The solid line shows the best-fitting light curve.

Table 1. Infrared magnitudes of UNSW-TR-2 and its close neighbour from the 2 Micron All Sky Survey (2MASS) catalogue.

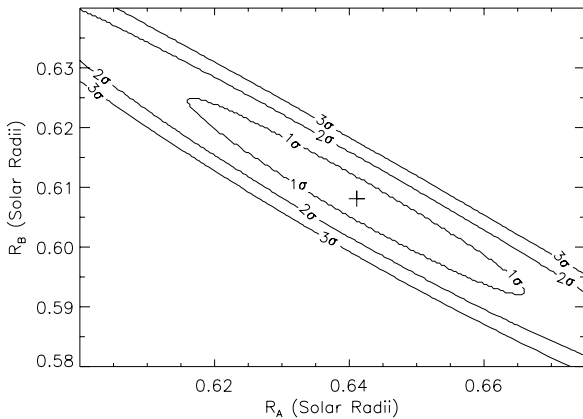
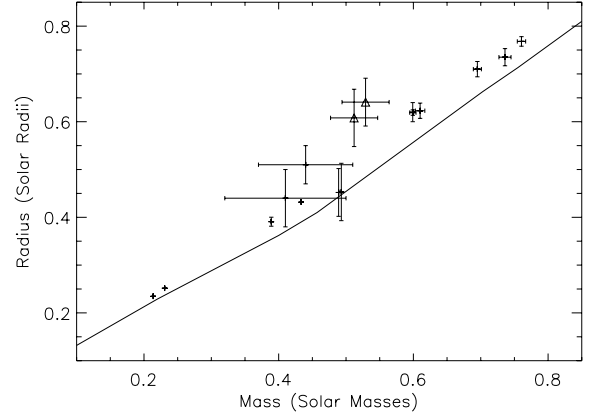
	TR-2	Neighbour
<i>J</i>	10.9	10.7
<i>H</i>	10.2	10.2
<i>K</i>	10.1	10.1

Table 2. Physical properties of UNSW-TR-2, derived from radial-velocity measurements (Section 2.2.2) and light-curve fitting (Section 3.2).

Period (d)	2.11674 ± 0.00002
t_0 (HJD)	$245\,3171.0371 \pm 0.0005$
Separation (au)	0.0327 ± 0.0007
Inclination ($^\circ$)	83.49 ± 0.2
M_{total} (M_\odot)	1.041 ± 0.06
M_A (M_\odot)	0.529 ± 0.035
M_B (M_\odot)	0.512 ± 0.035
ΔM (M_\odot)	0.017 ± 0.03
R_A (R_\odot)	0.641 ± 0.05
R_B (R_\odot)	0.608 ± 0.06
ΔR (R_\odot)	0.033 ± 0.06
T_B/T_A	0.980 ± 0.015

3.3 Error estimation

To estimate the uncertainties in our light-curve fit, we plotted R_A versus R_B reduced chi-squared contour plots for ranges of i , T_B/T_A and F either side of the best-fitting parameters (Fig. 3). The contours on each R_A versus R_B plot are ellipses, tightly constraining the sum of the radii but not their difference. Altering the other parameters from their best-fitting values decreases the size of the contours whilst moving their centre. Increasing i leads to a higher R_A but lower R_B , whilst increasing T_B/T_A has the opposite effect: lower R_A and higher R_B . We found that the flux ratio F is constrained relatively tightly and therefore contributes little to the uncertainties of the other parameters. Having scaled the errors such that the best-fitting reduced chi-squared has a value of one, the 1σ errors

**Figure 3.** The R_A versus R_B chi-squared contour plot around the best-fitting solution to the light curve. The other parameters are set to their best-fitting values. The three contours represent the 1σ , 2σ and 3σ confidence regions, but to estimate the true uncertainties T_B/T_A and i must also be varied.**Figure 4.** Mass versus radius for all known components of double-lined eclipsing binary stars with $M < 0.8 M_\odot$. UNSW-TR-2 is shown as triangles. The solid line is an approximation to a 300-Myr isochrone calculated with models from Baraffe et al. (1998). The figure is based on fig. 1 in Ribas (2005).

for the remaining four parameters were estimated by the range of the appropriate chi-squared contour over the full four-dimensional error ellipsoid. Further (minor) contributions to these errors come from the uncertainties in the velocity amplitude and limb-darkening coefficients. Because the estimates of the two radii are not independent, we also used the contour plots to derive an estimate of $\Delta R = R_A - R_B$.

4 RESULTS AND DISCUSSION

The parameters we have derived for UNSW-TR-2 from both the light-curve fitting and spectral analysis are shown in Table 2. The derived masses are consistent with our earlier estimate (based on spectral shape) of two K7 V stars. The star estimated to have a higher mass, radius and temperature corresponds to the component identified in Section 2.2.1 as having stronger absorption and emission features.

In Fig. 4, we plot the masses and radii of all the known components of detached, double-line eclipsing binaries with masses below $0.8 M_\odot$, including UNSW-TR-2. We also plot a theoretical main-sequence isochrone derived by Baraffe et al. (1998). As noted by Ribas (2005) and references therein, stars with masses greater than $\sim 0.3 M_\odot$ seem to fall systematically above the theoretical line, with their radii being underestimated by ~ 10 per cent. The two stars in UNSW-TR-2 appear to agree with this trend, although a more precise determination of their masses and radii is clearly required.

It is likely that one or both of our stars lies in the previously unpopulated region between 0.5 and $0.6 M_\odot$, which increases their importance in constraining the mass–radius relation of low-mass stars. The apparent magnitude of our system ($V \simeq 13.9$) is similar to that of the $0.6 M_\odot$ eclipsing binary GU Bootis ($V \simeq 13.7$), for which López-Morales & Ribas (2005) derived the masses and radii to within the 2–3 per cent accuracy required for a detailed comparison with theory. With echelle spectroscopy and further photometry, the properties of UNSW-TR-2 could therefore be similarly constrained.

4.1 UNSW-TR-2 as a target for a planet search

Eclipsing binary systems with dwarf components are interesting targets for photometric planet searches. One main advantage is

that the orbits of planets in such a system are likely to be near-coplanar with the binary, making transits more likely. Additionally, non-transiting planets may also be detected via the variations they induce in the timing of the binary eclipse minima (e.g. Doyle & Deeg 2004). These motivated an extensive search around the M-dwarf binary CM Dra (Doyle et al. 2000).

In the case of UNSW-TR-2, transits of a Jupiter-sized planet in front of one of the stars (when they are not eclipsing) would be 1.3 per cent deep. A planet in a coplanar orbit about the binary ($i = 83.5^\circ$) would have to be within $r_{\max} \simeq 0.04$ au of the centre of mass to transit. This is only 2.5 times the binary's semimajor axis, but according to simulations by Holman & Wiegert (1999), even such a small orbit may be stable around an equal-mass binary with a circular orbit. Planets with more favourable orbital inclinations (relative to the line of sight) may also transit. For example, $i_p = 85^\circ$ gives $r_{\max} = 0.05$ au, and $i_p = 87^\circ$ gives $r_{\max} = 0.09$ au.

The approximate range of eclipse-timing variations is $\tau = qr/c$, where q is the planet-to-binary mass ratio, r is the planet's orbital radius and c is the speed of light (Doyle & Deeg 2004). For a Jupiter-mass planet ($q \simeq 10^{-3}$) in a 1-au orbit, this gives $\tau \simeq 0.5$ s. The detection of planets via this method would therefore require second-precision timing of eclipses over time-scales of years.

5 CONCLUSIONS

We present a preliminary analysis of a new double-lined eclipsing binary system with K7 Ve components. The system was discovered as part of an ongoing transit search for extrasolar planets. The system is important in that it is only the seventh low-mass binary known, and because it allows precise determinations of the masses and radii of these low-mass stars. Using the initial photometric data, and follow-up photometry and spectroscopy, we derive the physical parameters of the system. Our results are consistent with previous work, confirming a departure in the mass-radius plane from the theoretical models of Baraffe et al. (1998). Enhanced magnetic activity – due to the high rotational velocities of stars in close binaries – may be responsible for this discrepancy (Ribas 2005).

We find statistically significant evidence – in fact the most significant in any known low-mass eclipsing binary system – for a small but non-zero eccentricity in this new binary system, suggesting the possibility of an additional companion.

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