UBV(RI)$_C$ photometry of transiting planet hosting stars

P. F. L. Maxted,[1]* C. Koen[2] and B. Smalley[1]

[1]*Astrophysics Group, Keele University, Keele, Staffordshire ST5 5BG*
[2]*Department of Statistics, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa*

ABSTRACT

We present new *UBV(RI)*$_C$ photometry of 22 stars that host transiting planets, 19 of which were discovered by the Wide Angle Search for Planets (WASP) survey. We use these data together with Two Micron All Sky Survey (2MASS) *JHK*$_S$ photometry to estimate the effective temperature of these stars using the infrared flux method. We find that the effective temperature estimates for stars discovered by the WASP survey based on the analysis of spectra are reliable to better than their quoted uncertainties.

Key words: techniques: photometric – techniques: spectroscopic – planetary systems.

1 INTRODUCTION

The transit of a planet across the face of its host star provides us with the opportunity to measure the properties of the planet in great detail. Essential to exploiting this opportunity is a good understanding of the host star itself. For example, a combined analysis of the transit light curve together with the spectroscopic orbit of the host star leads directly to a measurement of the host star density, $\rho_\star$, and the surface gravity of the planet (Seager & Mallén-Ornelas 2003; Southworth, Wheatley & Sams 2007). To estimate the mass and radius of the planet, an additional constraint is needed. The details of how the additional constraint is applied varies between different groups, but they generally share the common feature that an analysis of the spectrum is used to estimate the stellar effective temperature, $T_{\rm eff}$, stellar surface gravity, log g, and metallicity, [Fe/H],[1] and these are combined with the estimate of $\rho_\star$ to estimate the mass and radius of the star using either an empirical calibration or stellar models (Bakos et al. 2010; Enoch et al. 2010; Southworth 2010). The radius and mass of the planet then follow directly from the observed depth of the transit and Kepler's law, respectively.

Irrespective of the details, it is clear that the accurate characterization of the host star is essential for an accurate understanding of the planets that orbit it. Most transiting planets discovered to date have been found using wide-angle, ground-based photometric surveys such as WASP (Pollacco et al. 2006) and HATNet (Bakos et al. 2004). These surveys target stars with visual magnitudes in the approximate range of 8.5–13. One obstacle to the accurate characterization of these stars is the poor quality of the optical photometry that is generally available for stars of this brightness.

Accurate photometry for bright stars is available at infrared wavelengths (*JHK*$_S$) across the entire sky from the Two Micron All Sky

Survey (2MASS; Skrutskie et al. 2006) and in the Southern hemisphere from the DENIS survey (The DENIS Consortium 2005). The DENIS survey extends the available photometry to the *I* band. In the Northern hemisphere the CMC14 catalogue provides r'-band photometry (Evans, Irwin & Helmer 2002). In the optical regime, *BV* photometry is available for stars brighter than $V \approx 12$ from the Tycho-2 catalogue (Høg et al. 2000), although this catalogue is only complete to $V \approx 11$ and the photometric precision deteriorates rapidly for $V \gtrsim 9.5$. Accurate optical photometry provides flux measurements around the peak of the spectral energy distribution (SED) for solar-type stars, unlike infrared photometry that samples the Rayleigh–Jeans tail of the SED. Optical photometry is also sensitive to reddening and metallicity, both of which affect the blue end of the SED much more than the red end. Both these effects need to be accurately accounted for if the distance to the star is to be estimated from the photometric properties of the star, e.g. for kinematical studies. The combination of accurate optical and infrared photometry also makes it possible to make a robust and accurate estimate of the star's effective temperature using the infrared flux method (IRFM; Blackwell, Shallis & Selby 1979). Accurate optical photometry is also useful for planning follow-up observations, e.g. for estimating optimum exposure times.

In this paper we present new, high-quality photoelectric optical photometry for 22 planet hosting stars, mostly WASP discoveries in the Southern hemisphere. We use this photometry to make an independent check on the accuracy of the effective temperature estimates published for these stars based on the analysis of their spectra.

2 OBSERVATIONS

Observations were obtained with the South African Astronomical Observatory (SAAO) 0.5-m telescope and modular photometer (Kilkenny et al. 1988). This is a very stable and well-understood instrumental setup for obtaining standardized *UBV(RI)*$_C$ photometry (Bessell 2005). Observations were obtained in dark sky conditions over the course of two observing runs, 2010 September 9–12 and

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*E-mail: pflm@astro.keele.ac.uk
[1] [Fe/H] is the iron abundance relative to the Sun, metallicity is normally estimated by assuming that the abundances of other elements scales with the iron abundance.

Table 1. Photometry of 22 transiting planet hosting stars. N is the number of observations obtained. Standard errors are given for stars with three or more observations.

Star	V	$B-V$	$U-B$	$V-R$	$V-I$	N
WASP-2	11.788	0.897	0.604	0.488	0.932	2
WASP-4	12.463	0.783	0.362	0.405	0.782	2
WASP-5	12.136	0.705	0.281	0.380	0.727	2
WASP-7	9.483	0.460	0.015	0.267	0.528	2
WASP-8	9.773	0.747	0.369	0.404	0.788	2
WASP-15	10.918	0.495	0.008	0.295	0.579	3
	±0.003	±0.001	±0.008	±0.013	±0.012	
WASP-16	11.309	0.741	0.283	0.380	0.763	2
WASP-17	11.500	0.496	0.040	0.268	0.585	2
WASP-18	9.273	0.484	0.013	0.278	0.548	2
WASP-19	12.312	0.785	0.398	0.425	0.812	4
	±0.017	±0.004	±0.052	±0.007	±0.009	
WASP-22	11.708	0.603	0.139	0.323	0.638	2
WASP-25	11.848	0.727	0.253	0.380	0.764	2
WASP-26	11.099	0.621	0.145	0.344	0.690	2
WASP-28	12.148	0.596	0.033	0.329	0.690	2
WASP-29	11.207	1.087	1.061	0.620	1.119	2
WASP-31	11.937	0.513	−0.009	0.297	0.593	3
	±0.006	±0.017	±0.004	±0.016	±0.004	
WASP-34	10.366	0.684	0.224	0.364	0.716	3
	±0.012	±0.003	±0.011	±0.013	±0.015	
WASP-37[a]	12.717	0.628	0.022	0.337	0.699	2
WASP-39	12.100	0.803	0.370	0.426	0.852	3
	±0.012	±0.021	±0.040	±0.006	±0.021	
HAT-P-24	11.754	0.462	−0.017	0.260	0.518	2
HAT-P-27/	12.163	0.909	0.645	0.467	0.892	3
WASP-40	±0.011	±0.010	±0.009	±0.009	±0.016	
CoRoT-7[b]	11.718	0.849	0.915	0.437	0.827	3
	±0.003	±0.026		±0.012	±0.027	

[a]One discrepant measurement ignored.
[b]Only one reliable U-band measurement was obtained.

2011 March 5–12. Reduction of the instrumental magnitudes to the standard photometric system defined by the E-region standards of Menzies et al. (1989) followed the methods described in the appendix of Kilkenny et al. (1988). The observations are presented in Table 1.

3 ANALYSIS

We estimate the effective temperature of these stars using a simplified version of the IRFM (Blackwell et al. 1979). The essence of this method is to find values of the effective temperature, $T_{\rm eff}$, and angular diameter, θ, for which stellar atmosphere models simultaneously satisfy the observed value of the bolometric flux at the Earth, $\mathcal{F}_\odot$, and the observed flux at infrared wavelengths. Photometry covering the peak of the SED is important for an accurate estimate of $\mathcal{F}_\odot$ in solar-type stars. Some type of interpolation scheme is required to enable the integration of an SED that is only sparsely sampled by broad-band photometry. In our method we use numerical integration of the best-fitting model SED from a grid of stellar atmosphere models. The infrared flux of a solar-type star predicted by stellar models is insensitive to parameters such as surface gravity, metallicity and reddening or to the details of the model, so that the value of $T_{\rm eff}$ is almost model independent. In principle, the value of $T_{\rm eff}$

derived by our method could be improved by recalculating or interpolating the model SED used in the integration of $\mathcal{F}_\odot$ and iterating this process. In practice we find that further refinement of our $T_{\rm eff}$ estimate is not required. An estimate of the interstellar reddening is required for an accurate comparison of the model SED to the observed fluxes. In practice, we find that the effect of interstellar reddening is negligible for the majority of the stars we have studied.

We use the data provided by 2MASS (Skrutskie et al. 2006) to obtain the $JHK_{\rm S}$ magnitudes for our targets. For stars where we have access to the spectra, we have measured the equivalent width of the interstellar absorption features due to sodium near 589 nm and used the calibration of Munari & Zwitter (1997) to convert this to an estimate of the interstellar reddening, $E(B-V)$. We estimate the bolometric flux from the star by integrating the best-fitting model SED from grid of models at 250-K intervals in $T_{\rm eff}$ from Kurucz (1993). We use least-squares fitting of the model fluxes integrated over the appropriate bandpasses for all available optical and infrared magnitudes to determine the best-fitting model SED. For stars with three or more observations we use the standard errors on the means to determine the weights of the $UBV(RI)_{\rm C}$ data in the fit. We use linear regression on the apparent magnitudes and standard errors in each bandpass for these stars to determine a relationship between apparent magnitude and standard error for each bandpass, and then use this to assign a weight to the data for stars with fewer than three observations. For the conversion of magnitudes to fluxes we use the zero-point values from Bessell (1979) and Cohen, Wheaton & Megeath (2003).

We include the effect of interstellar reddening in the least-squares fit of the grid of model SEDs for stars where an estimate of $E(B-V)$ from the spectrum is available. The SEDs were dereddened using the analytical extinction expressions from Howarth (1983). For the two stars for which we do not have access to the spectra we assume $E(B-V) = 0$. For a typical star with $T_{\rm eff} \approx 6000$ K and $E(B-V) \approx 0.01$, neglecting the reddening results in an overestimate of $T_{\rm eff}$ by about 30 K. The effective temperature of the star is then estimated using each of the available J, H and $K_{\rm S}$ magnitudes independently, and the weighted average of these results is taken as the final value. We refer to this estimate of the effective temperature as $T_{\rm IRFM}$.

The values of $E(B-V)$ and $T_{\rm IRFM}$ are given in Table 2 together with published estimates of the effective temperature for each star based on the analysis of the spectrum, $T_{\rm spec}$.

4 DISCUSSION

For all 25 stars from the WASP survey a method based on an analysis of the Hα line has been used to measure $T_{\rm spec}$ (Smalley et al. 2011). There may be systematic errors in these $T_{\rm spec}$ estimates due to instrumental effects such as scattered light, the normalization of the spectra, etc., as well as systematic errors in the model stellar atmospheres used to analyse the Hα line. Similar issues will affect the $T_{\rm spec}$ estimates for stars from other sources. Bruntt et al. (2010b) have compared $T_{\rm spec}$ estimates for 23 nearby solar-type stars to $T_{\rm eff}$ determined directly from interferometric angular diameters. They find that their $T_{\rm spec}$ estimates are too hot by 40 ± 20 K.

Casagrande et al. (2010) report $T_{\rm eff}$ estimates for GK-type stars using the IRFM based on $BV(RI)_{\rm C}JHK_{\rm S}$ photometry similar to ours. They argue that the main source of systematic error in the IRFM method is the conversion of magnitudes to fluxes, i.e. the zero-point of the optical and infrared magnitude scales. They estimate that a 2 per cent error in the zero-point results in an error of approximately 40 K in $T_{\rm IRFM}$. Although our implementation of the IRFM is not the same in detail as that of Casagrande et al. this estimate of

Table 2. Effective temperature estimates for our target stars. The reddening $E(B - V)$ is estimated from the equivalent width of the interstellar sodium 'D' absorption lines.

Star	$E(B - V)$	T_{IRFM} (K)	T_{Spec} (K)	[Fe/H]	Spectrograph	Reference
WASP-2	0.02	5110 ± 60	5200 ± 200	~ 0.0	SOPHIE	Collier Cameron et al. (2007)
			5150 ± 80	-0.08 ± 0.08	HARPS	Triaud et al. (2010)
WASP-4	0.00	5540 ± 55	5500 ± 150	0.0 ± 0.2	CORALIE	Wilson et al. (2008)
			5500 ± 100	-0.03 ± 0.09	UVES	Gillon et al. (2009)
WASP-5	0.00	5770 ± 65	5700 ± 100	0.0 ± 0.2	CORALIE	Anderson et al. (2008)
			5700 ± 100	0.09 ± 0.09	UVES	Gillon et al. (2009)
WASP-7	0.00	6520 ± 70	6400 ± 100	0.0 ± 0.1	CORALIE	Hellier et al. (2009b)
WASP-8	0.00	5570 ± 85	5600 ± 80	0.17 ± 0.17	HARPS	Queloz et al. (2010)
WASP-15	0.00	6210 ± 60	6300 ± 100	1.4 ± 0.1	CORALIE	West et al. (2009)
WASP-16	0.01	5550 ± 60	5700 ± 150	0.01 ± 0.10	CORALIE	Lister et al. (2009)
WASP-17	0.05	6500 ± 75	6550 ± 100	-0.25 ± 0.09	CORALIE	Anderson et al. (2010)
			6650 ± 80	-0.19 ± 0.09	HARPS	Triaud et al. (2010)
WASP-18	0.00	6455 ± 70	6400 ± 100	0.00 ± 0.09	HARPS	Hellier et al. (2009a)
WASP-19	0.00	5440 ± 60	5500 ± 100	0.02 ± 0.09	CORALIE	Hebb et al. (2010)
WASP-22	0.01	6020 ± 50	6000 ± 100	0.05 ± 0.08	HARPS	Maxted et al. (2010)
WASP-25	0.00	5615 ± 55	5750 ± 100	-0.05 ± 0.10	CORALIE	Enoch et al. (2011)
WASP-26	0.01	6015 ± 55	5950 ± 100	-0.02 ± 0.09	CORALIE	Smalley et al. (2010)
WASP-28	0.04	6190 ± 60	6100 ± 150	-0.29 ± 0.10	CORALIE	West et al. (2010)
WASP-29	0.00	4875 ± 65	4800 ± 150	0.11 ± 0.14	CORALIE	Hellier et al. (2010)
WASP-31	0.00	6175 ± 70	6250 ± 150	-0.29 ± 0.11	CORALIE	Anderson et al. (2011a)
			6300 ± 100	-0.20 ± 0.09	HARPS	Anderson et al. (2011a)
WASP-34	0.00	5695 ± 65	5700 ± 100	-0.02 ± 0.10	CORALIE	Smalley et al. (2011)
WASP-37	0.05	5940 ± 55	5800 ± 150	-0.40 ± 0.12	CORALIE+SOPHIE	Simpson et al. (2011)
WASP-39	0.04	5460 ± 55	5400 ± 150	-0.12 ± 0.10	CORALIE	Faedi et al. (2011)
HAT-P-24		6330 ± 65	6373 ± 80	-0.16 ± 0.08	HIRES	Kipping et al. (2010)
HAT-P-27		5175 ± 70	5300 ± 90	0.29 ± 0.10	HIRES	Béky et al. (2011)
=WASP-40	0.01		5200 ± 150	0.14 ± 0.11	CORALIE+SOPHIE	Anderson et al. (2011b)
CoRoT-7		5240 ± 55	5275 ± 75	0.03 ± 0.06	UVES	Léger et al. (2009)
			5250 ± 60	0.12 ± 0.06	HARPS+UVES	Bruntt et al. (2010a)
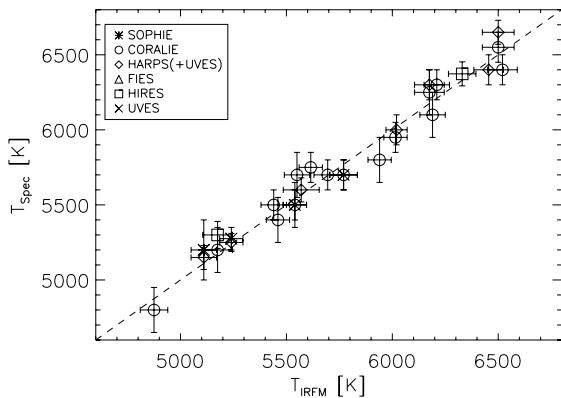
Figure 1. Comparision of effective temperature estimates using the IRFM and from spectroscopy.

the systematic error inherent in the method applies equally to our method.

A comparison of the effective temperature estimates T_{IRFM} and T_{spec} is shown in Fig. 1. The mean value of $T_{spec} - T_{IRFM}$ is (-13 ± 17) K. It can be seen that the agreement between the two temperature scales is very good. The χ^2 value for the 1:1 relation shown in Fig. 1 is 12.2 for 29 degrees of freedom. This level of agreement is much better than would be expected given the standard errors quoted for T_{IRFM} and T_{spec}. However, the uncertainties quoted for T_{spec} for all the WASP stars (25 of the 29 T_{spec} values) include some estimate of the systematic error in the estimate and these uncertainties are

generally quoted to the nearest 50 K, e.g. ± 100 K. If we assume that any systematic error in T_{IRFM} is about 40 K; this suggests that the systematic error in T_{spec} for WASP stars is likely to be $\lesssim 50$ K, i.e. similar to the level of systematic error found by Bruntt et al. for their T_{spec} estimates.

Another quantity sometimes estimated from T_{spec} is $(B - V)_0$, the intrinsic $B - V$ colour. This is used to calculate the chromospheric activity index $\log R'_{HK}$ (Noyes et al. 1984). For WASP stars the calibration of Gray (2008) is used to estimate $B - V$ from T_{spec} (e.g. Maxted et al. 2011). For the 19 WASP stars here, we find that this estimate is accurate to better than 0.03 mag. This corresponds to an additional uncertainty of about 0.05 in the value of $\log R'_{HK}$, which is small compared to the intrinsic decadal variability in this quantity for these types of stars.

5 CONCLUSIONS

We have used $UBV(RI)_C$ photometry combined with published infrared photometry to show that the effective temperature estimates for planet hosting stars discovered by the WASP survey based on the analysis of the spectrum are consistent with the IRFM effective temperature scale to better than the quoted standard errors, typically ± 100 K.

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