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Letter to the Editor

Effective temperatures and radii of planet-hosting stars from IR photometry

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Abstract. In this paper we present and analyse determinations of effective temperatures of planet-hosting stars using infrared (IR) photometry. One of our goals is the comparison with spectroscopic temperatures to evaluate the presence of systematic effects that could alter the determination of metal abundances. To estimate the stellar temperatures we have followed a new approach based on fitting the observed 2MASS IR photometry with accurately calibrated synthetic photometry. Special care has been put in evaluating all sources of possible errors and incorporating them in the analysis. A comparison of our temperature determinations with spectroscopic temperatures published by different groups reveals the presence of no systematic trends and a scatter compatible with the quoted uncertainties of 0.5–1.3%. This mutual agreement strengthens the results of both the spectroscopic and IR photometry analyses. Comparisons with other photometric temperature calibrations, generally with poorer performances, are also presented. In addition, the method employed of fitting IR photometry naturally yields determinations of the stellar semi-angular diameters, which, when combined with the distances, results in estimations of the stellar radii with remarkable accuracies of ~2–4%. A comparison with the only star in the sample with an empirically determined radius (HD 209458 – from transit photometry) indicates excellent agreement.

Key words. stars: fundamental parameters – stars: late-type – stars: abundances – infrared: stars – techniques: photometric

1. Introduction

The characterization of the properties of planet-hosting stars has been an active field of study. Soon after the discovery of the first candidates, claims were made that stars with planets displayed on average higher metal contents (Gonzalez 1997) than other solar neighbourhood stars. A number of subsequent independent studies with increasingly large stellar samples have mostly confirmed the initial claims (e.g. Santos et al. 2003). An important point to be made is that the determination of chemical abundances, mostly carried out through detailed analysis of spectroscopic data, is quite challenging (see Gonzalez 2003 for a complete review). As it has been shown for late-type stars (i.e. FGK planet hosts), a strong degeneracy affecting the determination of metal abundances is the correlation with effective temperature. Straightforward estimations show that a systematic error of +100 K in $T_{\rm eff}$ (i.e. 1.5–2% at the temperatures of FGK stars) results in metal abundances being systematically overestimated by +0.06 dex (~15%). Most studies of stellar atmospheric parameters carry out multiple fits to derive chemical compositions and effective temperatures from the spectra. Although the aforementioned correlation would not alter the conclusions of relative studies including both planet-hosting and non-planet hosting stars, the metal richness of the stars would be systematically biased when compared to the Sun. Another point worth making is the use by present spectroscopic studies of solar line oscillator strengths for all late-type stars (e.g. Gonzalez & Laws 2000). This might introduce systematic errors for temperatures below and above that of the Sun that thus far have not been addressed in detail.

The potential problems with spectroscopic analyses discussed above make a completely independent temperature determination, for example using photometry, very valuable. The absence of systematic effects when comparing photometric and spectroscopic temperatures would strengthen the case for the metal richness of planet-bearing stars and support the use of solar oscillator strengths over the relevant spectral type range. However, the determination of photometric temperatures for cool stars (below 7000 K) is not straightforward because most photometric systems are not designed for such low temperatures. For example, although some efforts have been made to extend the temperature range covered by Strömgren calibrations down to late-type stars (Olsen 1984), most of the work is

Send offprint requests to: I. Ribas, e-mail: iribas@am.ub.es still in a preliminary stage. Here we present a new approach, namely the determination of effective temperatures from infrared (IR) photometry. The underlying idea is similar to the Infra-Red Flux Method (IRFM), proposed and implemented by Blackwell & Shallis (1977), Blackwell et al. (1980) and later Alonso et al. (1996).

In this paper we briefly discuss the proposed approach and compare our results with spectroscopic temperature determinations. In addition, the analysis also yields an robust and accurate determination of the stellar radius, provided the distance is known. With the release of the 2MASS All Sky Catalog[1], which contains IR photometry covering the entire sky, the proposed method has a wide applicability, thus permitting accurate (a few percent) and effortless determinations of temperatures and radii (important for transits) of planet-hosting stars.

2. The stellar sample

Planet searching projects are currently so efficient that the number of planet-hosting stars increases on a weekly basis. Our starting sample was complete as of July 2003 and comprised 94 stars with planets, which makes up a statistically significant number for our comparisons. The original list was cross-matched with the 2MASS All Sky Catalog with a 100% success rate. In a next step, we excluded those stars with poor-quality photometry in all of the three 2MASS bands, generally because of strong saturation[2]. As a criterion, we rejected stars with errors in the K band (the band with best quality for bright stars) greater than 0.05 mag. In addition, two stars were excluded for different reasons: HD 113020, classified as spectral type M4, because its temperature is expected to be below 4000 K and beyond the studied temperature range; and OGLE-TR56, the farthest known planet-hosting star at 1.5 kpc, because of concerns with the extinction correction. The final working sample is therefore composed of 81 planet-bearing stars, which are listed in Table 1.

The 2MASS photometry was complemented with V standard measurements (together with their uncertainties) obtained from GCPD (Mermilliod et al. 1997). Also from GCPD we compiled Strömgren photometry and carried out an estimation of the reddening correction. All stars were found to fall right on the standard relationships as defined by Crawford (1975) and Olsen (1984, 1988), i.e. zero reddening as expected from their nearby distances within 100 pc.

3. Determination of temperatures and radii

The use of IR photometry for determining effective temperatures was initially proposed by Blackwell & Shallis (1977). Their so-called IRFM uses the ratio between the bolometric flux of the star and the monochromatic at a given wavelength in the IR, both measured at the Earth, as the observable quantity. This ratio is compared with a theoretical estimate derived from atmosphere models, allowing the determination of the effective temperature. The method we have developed follows a somewhat different approach, namely, a fit of the stellar spectral energy distribution from the optical (V) to the IR (JHK) with synthetic photometry computed from atmosphere models. This wavelength range ensures enough sensitivity to temperature, while being essentially immune to intrinsic variations (mostly due to chromospheric activity) that would strongly affect bluer passbands. Also importantly, the spectral energy distribution in the optical/IR for cool stars is mostly insensitive to the (often unknown) values of $\log g$ and [Fe/H]. In contrast to the IRFM, our method does not require the use of a bolometric flux calibration, thus reducing the risk of uncontrolled systematic errors, and permits the determination of individual uncertainties. The algorithm will be discussed in detail by Masana (2004) but we briefly outline the procedure here.

A critical pre-requisite to compare stellar and model fluxes is a well-characterized photometric system and an accurate flux calibration. Fortunately, the recent work by Cohen et al. (2003a,b) provides a set of consistent absolute flux calibrations in both the optical (Landolt system) and IR (2MASS). To compute synthetic magnitudes we employ the dense grid of Kurucz atmosphere models[3], although tests with other models (discussed below) reveal negligible differences. The synthetic $VJHK$ photometry was calculated for each of the grid points as a function of $T_{\rm eff}$, [Fe/H], and $\log g$. We restricted our calculations to the temperature interval between 4000 and 8000 K. The upper limit is defined by the increasing dependence of the results on $\log g$ and the lower limit is set by the decreasing performance of the models because of molecular bands.

The algorithm itself is based on the minimisation of a χ^2 function defined from the difference between the observed and synthetic $VJHK$ magnitudes. The two adjustable parameters are $T_{\rm eff}$ and a magnitude zeropoint (ZP), while $\log g$ and [Fe/H] are fixed input data (recall that interstellar absorption for our stars is negligible). The ZP is the difference between the synthetic (star's surface) and the observed magnitude (Earth surface), and it is directly related to the semi-angular diameter ($\theta = 10^{-0.2\,{\rm ZP}}$). The input values of [Fe/H] were taken from the spectroscopic determinations and $\log g$ was roughly estimated from stellar models (in the $T_{\rm eff}$–L plane) after one iteration. Convergence towards the minimum value of the reduced χ^2 was very fast and reached values close to unity.

Perhaps the greatest advantage of our method is that it yields the individual uncertainties of both $T_{\rm eff}$ and θ, calculated from the covariance matrix, provided the involved errors are realistically estimated. For the present sample, the error sources considered are: 1) observed magnitude errors, with an minimum 0.015 mag error in V (usually computed from the average of a few measurement and thus prone to error underestimation); 2) zero point uncertainties in the flux calibration (1.5−1.7%) from Cohen et al. (2003a,b); 3) conservative error bars of 0.1 dex in [Fe/H] and 0.2 dex in $\log g$ dex[4]; 4) no

[1] http://www.ipac.caltech.edu/2mass

[2] The 2MASS team managed to extract good quality photometry from the wings of mildly saturated stars, which led to a significant increase in dynamic range (see Cutri et al. 2003). In general, good photometry was obtained for stars with $K > 4$ mag.

[3] http://kurucz.harvard.edu/grids.html

[4] Our method is essentially insensitive to the adopted value of [Fe/H] and $\log g$. Thus, uncertainties up to 0.3 dex in [Fe/H] and 0.5 dex in $\log g$ introduce uncertainties in $T_{\rm eff}$ below 0.5%.

error was attributed to the model fluxes. We ran a number of comparison with other (less dense) atmosphere model grids such as those by Castelli et al. (1997) and the NextGen models by Hauschildt et al. (1999). Our tests were extremely satisfactory and yielded average temperature differences below 15 K (∼0.3%) in all cases. Thus, systematic errors introduced by atmosphere models are likely to be negligible.

The procedure described above yields two basic parameters: The best-fitting effective temperature and semi-angular diameter (i.e. radius/distance). With a known distance, the latter can be transformed into a true radius measurement. The results for our stellar sample are listed in Table 1. The relative accuracy of the results is 0.5–1.3% in effective temperature and 0.9–2.4% in semi-angular diameter. Since the planet-hosting stars in the sample are generally nearby, their Hipparcos distances are very accurate. This results in relative uncertainties in the individual radii in the range of 1.3–4.7% for 90% of the stars.

4. Discussion

With the temperatures from IR photometry in hand, we carried out a comparison with spectroscopic determinations to assess their mutual agreement. We considered two comprehensive and independent spectroscopic analyses, following, however, similar approaches: The Swiss group (Santos et al. 2001, 2003) and the US group (Gonzalez 1997–1999; Gonzalez & Laws 2000; Gonzalez et al. 2001; Feltzing & Gonzalez 2001; Laws et al. 2003). A cross-match of the IR and spectroscopic samples yields a total of 69 stars in common with the Swiss group and 49 with the US group. The resulting comparisons are illustrated in Fig. 1, where the observational data are plotted with their error bars. As can be seen, the agreement among the three temperature determinations is very remarkable. The mean difference between the IR-based and the Swiss group temperatures is $< T_{\rm eff\,IR} - T_{\rm eff\,SW} > = -4.2 \pm 51.4$ K, with no hint of any systematic trends neither as a function of temperature, metallicity or surface gravity. The difference with the US group yields a value of $< T_{\rm eff\,IR} - T_{\rm eff\,US} > = +20.5 \pm 65.9$ K, with a low significance trend of larger IR temperatures at the low $T_{\rm eff}$ end and smaller IR temperatures at the high $T_{\rm eff}$ end. No systematic trends are seen as a function of metallicity or surface gravity. Interestingly, in both cases the scatter of the differences is entirely consistent with the quoted error bars, which indicates that our procedure yields realistic uncertainties.

A valuable independent test of our analysis can be carried out by comparing the semi-angular diameters with observational determinations. Unfortunately, this is not possible at this point because all the stars with available empirical angular diameter measurements are very bright (see Alonso et al. 1994 for a compilation) and do not have accurate 2MASS photometry. Luckily, there is one star in our sample with an accurate empirical radius measurement and this is HD 209458, which undergoes planetary transits. Generally it is very difficult to disentangle the stellar and the planetary radii effects when analyzing transit light curves. However, Brown et al. (2001) were able to determine both the stellar radius and the planetary radius simultaneously from a high precision transit light curve of

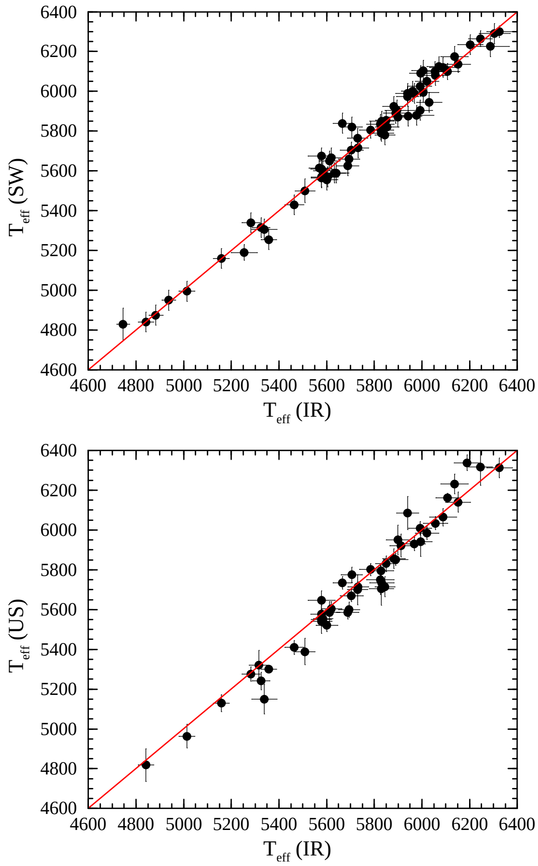

Fig. 1. Comparison of effective temperatures determined using our method (IR) and temperatures determined spectroscopically by the Swiss (SW) and US groups (see text for references).

HD 209458 obtained with the Hubble Space Telescope. Their empirically-determined radius is $1.146 \pm 0.050\ R_\odot$, which can be compared with our estimate of $1.145 \pm 0.049\ R_\odot$ from the fit to the star's optical/IR energy distribution. The agreement is excellent (owing the almost null difference to small number statistics) and the error bars of both measurements are alike.

These important results indicate that our temperature and radius determination method is robust and with a very similar accuracy to the one possibly achievable with the best available spectroscopy and photometry today.

For completeness, the effective temperatures in Table 1 were also compared with those computed from photometric calibrations. A detailed discussion is left for a forthcoming publication, but we shall briefly review here some of the most relevant results. Our tests focused on the Strömgren calibrations of Olsen (1984) and the IRFM as implemented by Alonso et al. (1996). The comparisons show that the $(b-y)$ calibration of Olsen (1984) yields effective temperatures that are systematically lower than those resulting from our method, with the mean difference being 168 ± 103 K. Interestingly, a marked trend was found when plotting the differences as a function of metallicity. It seems that the origin of the discrepancies can be ascribed to the stellar sample used to derive the Strömgren calibrations, since only one third of Olsen's reference stars have super-solar metallicities. In contrast, the comparison with the temperatures derived from the IRFM calibration of

Table 1. Effective temperatures, semi-angular diameters ($\theta \equiv$ radius/distance) and radii, with their uncertainties, of planet-hosting stars as resulting from the algorithm discussed in this paper.

HD	$T_{\rm eff}$ (K)		θ (mas)		R ($R_\odot$)		HD	$T_{\rm eff}$ (K)		θ (mas)		R ($R_\odot$)		HD/BD	$T_{\rm eff}$ (K)		θ (mas)		R ($R_\odot$)	
142	6304	± 65	0.255	± 0.005	1.404	± 0.029	68988	5911	± 47	0.094	± 0.001	1.183	± 0.044	145675	5357	± 32	0.251	± 0.003	0.978	± 0.013
1237	5600	45	0.224	0.003	0.849	0.013	72659	5912	52	0.132	0.002	1.454	0.057	147513	5978	70	0.337	0.008	0.933	0.024
2039	5940	50	0.063	0.001	1.227	0.085	73256	5480	39	0.121	0.002	0.950	0.017	150706	5961	47	0.160	0.002	0.938	0.016
3651	5394	56	0.347	0.008	0.829	0.020	73526	5661	46	0.073	0.001	1.491	0.106	162020	4745	26	0.116	0.001	0.783	0.037
4208	5688	46	0.125	0.002	0.879	0.025	74156	6006	50	0.118	0.002	1.638	0.092	168443	5584	40	0.194	0.002	1.582	0.051
4203	5611	43	0.084	0.001	1.411	0.112	75289	6151	52	0.200	0.003	1.243	0.022	168746	5577	44	0.121	0.002	1.124	0.045
6434	5829	51	0.122	0.002	1.060	0.030	75732	5338	53	0.343	0.008	0.925	0.023	169830	6325	54	0.230	0.003	1.799	0.060
8574	6056	51	0.145	0.002	1.380	0.049	76700	5670	46	0.106	0.001	1.367	0.053	177830	4841	31	0.257	0.003	3.268	0.091
10697	5620	42	0.256	0.004	1.796	0.051	80606	5605	43	0.074	0.001	0.927	0.304	178911	5630	42	0.114	0.001	1.145	0.502
12661	5732	43	0.144	0.002	1.154	0.035	82943	5992	48	0.193	0.002	1.138	0.028	179949	6202	52	0.205	0.003	1.193	0.030
13445	5253	54	0.333	0.008	0.781	0.019	83443	5508	41	0.110	0.001	1.034	0.034	186427	5729	42	0.251	0.003	1.154	0.019
16141	5785	47	0.185	0.003	1.428	0.047	89744	6189	55	0.260	0.004	2.181	0.055	187123	5849	45	0.114	0.001	1.179	0.032
17051	6286	80	0.296	0.007	1.097	0.029	92788	5705	44	0.152	0.002	1.055	0.033	190228	5282	37	0.191	0.002	2.555	0.065
20367	6055	52	0.202	0.003	1.182	0.029	106252	5889	51	0.136	0.002	1.092	0.041	190360	5639	53	0.326	0.006	1.113	0.023
23079	6030	52	0.149	0.002	1.106	0.022	108147	6245	50	0.144	0.002	1.193	0.028	192263	5013	33	0.178	0.002	0.760	0.019
23596	6071	51	0.137	0.002	1.530	0.057	108874	5568	43	0.084	0.001	1.232	0.082	195019	5666	39	0.191	0.002	1.538	0.041
28185	5704	48	0.122	0.002	1.041	0.038	114386	4883	29	0.124	0.002	0.750	0.028	196050	5894	49	0.129	0.002	1.306	0.037
30177	5633	47	0.096	0.002	1.130	0.049	114762	5899	50	0.146	0.002	1.273	0.053	209458	6088	56	0.113	0.002	1.145	0.049
33636	5967	46	0.159	0.002	0.984	0.032	114783	5157	33	0.179	0.002	0.788	0.018	210277	5578	43	0.232	0.003	1.061	0.021
37124	5577	43	0.140	0.002	1.004	0.039	114729	5853	49	0.194	0.003	1.462	0.050	213240	5939	46	0.175	0.002	1.533	0.039
39091	6006	64	0.290	0.006	1.138	0.025	121504	5994	47	0.122	0.002	1.167	0.035	216435	5992	50	0.245	0.004	1.753	0.042
38529	5578	57	0.305	0.007	2.784	0.108	128311	4936	28	0.214	0.002	0.762	0.013	216437	5942	56	0.247	0.004	1.409	0.030
40979	6223	55	0.165	0.002	1.183	0.032	130322	5464	39	0.123	0.002	0.787	0.030	217014	5827	52	0.343	0.006	1.133	0.022
46375	5324	37	0.140	0.002	1.005	0.036	134987	5844	42	0.214	0.002	1.178	0.028	217107	5694	44	0.260	0.004	1.103	0.022
49674	5642	41	0.111	0.001	0.968	0.040	136118	6136	57	0.154	0.002	1.736	0.071	222582	5831	50	0.123	0.002	1.107	0.044
50554	6020	49	0.167	0.002	1.117	0.035	141937	5881	47	0.146	0.002	1.052	0.039	−02 5917B	5542	51	0.094	0.002	1.100	0.120
52265	6107	50	0.208	0.003	1.258	0.031	143761	5825	57	0.354	0.006	1.327	0.027	−10 3166	5315	40	0.052	0.001	–	

Alonso et al. (1996) reveals no systematic trends but they are on average 76 ± 42 K smaller than our determinations. Given the similarity of both methods and input data, the discrepancy can tentatively be attributed to the photometric transformations employed or to the bolometric flux calibration used by Alonso et al. (1996).

5. Conclusions

The conclusions of our study are twofold. First, we have compared the effective temperature determinations for planet-bearing stars from two completely independent approaches with similar accuracies, namely detailed spectroscopic analysis and IR photometry. The results indicate an excellent agreement in the entire temperature range, which confidently rules out the possibility of systematic effects in spectroscopic metallicity determinations and supports the use of solar line oscillator strengths. Second, the method presented, consisting in a fit to the observed *VJHK* magnitudes using synthetic magnitudes, has proved its reliability, yielding accurate (∼1%) and cost-effective temperatures. As a bonus, the analysis also provides determinations of the semi-angular diameters and, eventually, the stellar radii. The resulting radius accuracy of a few percent (for nearby stars) could be extremely useful to break the strong degeneracy between the radii of the planet and the star when analysing transit light curves.

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