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 $T_{\text{eff}}$ (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 calibra-
tions down to late-type stars (Olsen 1984), most of the work is 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 Infra-Red Flux Method (IRFM), proposed and implemented by infrared (IR) photometry. The underlying idea is similar to the namly the determination of e...
error bars of 0.1 dex in $[\text{Fe}/\text{H}]$ and 0.2 dex in $\log g$ dex$^4$; 4) No 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 I. 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, 1998, 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. II 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 $< T_{\text{eff,IR}} - T_{\text{eff,SW}} > = -4.2 \pm 51.4$ 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 $< T_{\text{eff,IR}} - T_{\text{eff,US}} > = +20.5 \pm 65.9$ K, with a low significance trend of larger IR temperatures at the low $T_{\text{eff}}$ end and smaller IR temperatures at the high $T_{\text{eff}}$ 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 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 I 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

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$^4$ Our method is essentially insensitive to the adopted value of $[\text{Fe}/\text{H}]$ and $\log g$. Thus, uncertainties up to 0.3 dex in $[\text{Fe}/\text{H}]$ and 0.5 dex in $\log g$ introduce uncertainties in $T_{\text{eff}}$ below 0.5%.
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 Alonso et al. (1996) reveals no systematic trends but they are on average 76±47 K smaller than our determinations. Given the behavior 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 for the entire temperature range, which confidently rules out the possibility of systematic errors 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.