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The effective temperature scale: resolving different versions

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Abstract. The effective temperature of a stellar surface is a measure of the total energy and its correct characterization plays a central role in both theory and observations. Various effective temperature scales have been proposed in literature. Despite being such a long-lived tradition and the high internal precision usually achieved, systematic differences of order 100 K among various scales are still present, thus hindering much of a progress in the field. We present an Infrared Flux Method based investigation aimed to carefully assess the sources of such discrepancies and pin down their origin. We break the impasse among different scales by using a large set of solar twins, stars which are spectroscopically and photometrically identical to the Sun, to set the zero-point of the effective temperature scale to within few degrees. Our newly calibrated, precise and accurate temperature scale applies to dwarfs and subgiants, from super solar metallicities to the most metal poor stars currently known. The effect of using spectral energy distribution computed from 3D models in the Infrared Flux Method, as well as 3D synthetic colours are also briefly outlined.

Key words. Stars: fundamental parameters – Stars: abundances – Stars: atmospheres – Infrared: stars – Techniques: photometric

1. Introduction

The determination of effective temperatures ($T_{\rm eff}$) in F, G and K type stars is of paramount importance for reliable abundance analyses and thus for improving our understanding of Galactic chemical evolution. Several indirect methods of $T_{\rm eff}$ determination have been devised to avoid the complications introduced by the measurement of stellar angular diameters, which are necessary to derive $T_{\rm eff}$ from basic principles. Thus, most published values of $T_{\rm eff}$ are model-dependent or based on empirical calibrations that are not free from systematics themselves.

It is therefore not surprising to find discrepancies among published $T_{\rm eff}$ values. The ionization and excitation balance of iron lines in a 1D LTE analysis is routinely used to derive effective temperatures as well as $\log g$ and [Fe/H] . While for a sample of stars with similar properties this method can yield highly precise relative physical parameters, non-LTE effects and departures from homogeneity can seriously undermine effective temperature determinations, especially in metal-poor stars (e.g. Asplund 2005). Another popular method for deriving $T_{\rm eff}$ in late-type stars is provided by the study of the hydrogen Balmer lines, in particular Hα and Hβ (e.g. Nissen et al. 2007). For H lines, uncertainties related to observations, line

Send offprint requests to: L. Casagrande broadening, non-LTE and granulation effects all influence the estimation of effective temperatures (e.g Asplund 2005; Barklem 2007).

In such a scenario, an almost model independent and elegant technique for determining effective temperatures was introduced in the late 70's by Blackwell and collaborators under the name of InfraRed Flux Method (hereafter IRFM, Blackwell & Shallis 1977; Blackwell et al. 1979, 1980). Since then, a number of authors has applied the IRFM to determine effective temperatures in stars with different spectral types and metallicities. The main ingredient of the IRFM is infrared photometry, with the homogeneous and all–sky coverage provided by 2MASS being the standard choice nowadays (Ramírez & Meléndez 2005; Casagrande et al. 2006; González Hernández & Bonifacio 2009). Whilst the IRFM has high internal precision and is essentially immune from non-LTE and granulation effects, the absolute flux calibration adopted in such a technique can easily introduce a systematic as large as 100 K (Casagrande et al. 2006).

In order to provide a solution to different IRFM effective temperature scales currently available in literature we resort on solar twins to set the absolute zero point of the $T_{\rm eff}$ scale. This result is further validated using interferometric angular diameters and space-based spectrophotometry. Full details are available in (Casagrande et al. 2009)

2. The IRFM

The basic idea of the IRFM is to compare the ratio between the bolometric flux $\mathcal{F}_{Bol}$(Earth) and the infrared monochromatic flux $\mathcal{F}_{\lambda}$(Earth), both measured at Earth (the so called observational $R_{\rm obs}$ factor) to the ratio between the surface bolometric flux ($\sigma T_{\rm eff}^4$) and the surface infrared monochromatic flux $\mathcal{F}_{\lambda}$(model), predicted from model atmospheres. The ratio of the last two quantities defines the theoretical $R_{\rm theo}$ factor. From this comparison $T_{\rm eff}$ can be computed iteratively. In our implementation, the bolometric flux is derived from multi-band photometry, using 1D theoretical model atmospheres to estimate the flux outside the photometric bands. In the IRFM, more than one infrared band is normally used (in our case JHK_S from 2MASS), and the procedure described here is applied to each band separately. At each iteration the average $T_{\rm eff}$ obtained from all infrared bands is computed, until convergence is reached. Synthetic photometry is used as sanity check of the adopted implementation, to ensure that the effective temperatures and luminosities of the underlying synthetic spectra are recovered exactly.

The main ingredient in setting the zero point of any IRFM $T_{\rm eff}$ scale is the absolute calibration used for deriving bolometric and infrared fluxes from the observed photometry. Currently this is accurate at the $1-2\%$ level (Bohlin 2007), implying possible systematic uncertainties up to 40 K. The fundamental flux calibrator is Vega, which has been historically difficult to standardize (e.g. Gray 2007). Therefore, in literature it is possible to find much larger differences than the aforementioned uncertainty in the adopted absolute calibration. Those differences are entirely responsible for understanding the origin of different effective temperature scales.

2.1. Solar twins

Solar twins offer an approach independent on the absolute calibration of Vega to set the zero point of the $T_{\rm eff}$ scale with high accuracy. Our twins were drawn from an initial sample of about 100 stars broadly selected to be solar like: the identification of the best ones was based on a strictly differential analysis of high-resolution ($R \sim 60000$) and high signal-to-noise ($S/N \gtrsim 150$) spectra with respect to the solar one reflected from an asteroid and observed with the same instrument. Within this initial sample, the selection criterion adopted to identify the best twins did not assume any *a priori* effective temperature or colour, but was based on the measured relative difference in equivalent widths with respect to the observed solar reference spectrum and thus entirely model independent (Meléndez et al. 2006; Meléndez & Ramírez 2007).

Ten stars were identified as most closely resembling the Sun, including HIP56948, the best solar twin currently known (Meléndez & Ramírez 2007; Takeda & Tajitsu 2009). We determined $T_{\rm eff}$ via IRFM for each of them, imposing the mean effective temperature of all solar twins to equal $T_{\rm eff,\odot}$. We estimate the uncertainty on the zero point of our temperature scale to be 15 K based on a bootstrap procedure with one million re-samples.

2.2. Interferometric angular diameters and HST spectrophotometry

The IRFM determines $T_{\rm eff}$ in an almost model independent way, primarily recovering the bolometric flux $\mathcal{F}_{Bol}$(Earth) of the star under investigation. From the basic definition linking those two quantities the stellar angular diameter $\theta_{\rm IRFM}$ can be obtained self-consistently. This information is used to further validate our results.

All dwarfs and subgiants with reliable interferometric angular diameters are brighter than $V \simeq 6$, implying infrared magnitudes $\lesssim 5$ where 2MASS photometry has large observational errors and starts to saturate. Therefore it is not possible to apply the IRFM directly on them to get $\theta_{\rm IRFM}$. Instead, we adopt an indirect but fully consistent approach, using the photometric $T_{\rm eff}$:colour and $\mathcal{F}_{Bol}$:colour relations obtained with our implementation of the IRFM.

Despite difficulties and uncertainties that might still affect the comparison of angular diameters (Casagrande 2008; Casagrande et al. 2009) the average difference in angular diameter is -0.62 ± 1.70 % which corresponds to a zero point difference in the effective temperature scale of only $+18 \pm 50$ K at solar temperature. This is also in agreement with the uncertainty on the zero point of our temperature scale estimated using solar twins.

The CALSPEC library contains composite stellar spectra measured by the STIS and NICMOS instruments on board of the HST and used as fundamental flux standards. Free of any atmospheric contamination the HST thus provides the best possible spectrophotometry to date, with $1-2\%$ accuracy, extending from the far-UV to the near infrared. The absolute flux calibration is tied to the three hot, pure hydrogen white dwarfs, which constitute the HST primary calibrators, normalized to the absolute flux of Vega at 5556 Å. Thus, except for the normalization at 5556 Å the absolute fluxes measured by STIS and NICMOS are entirely independent on possible issues regarding Vega's absolute calibration in the infrared and offer an alternative approach to the 2MASS calibration underlying our temperature scale. Two of the CALSPEC targets are late-type main-sequence dwarfs for which accurate photometry is available: the metal-rich exoplanet host star HD209458 and the metal-poor fundamental SDSS standard BD+17 4708. For these stars, the continuum characteristics approximately longward of the Paschen discontinuity depend almost exclusively on the effective temperature, relatively unaffected by spectral lines, non-LTE effects as well as from the treatment of convection. The comparison of the HST absolute spectrophotometry of these two stars with synthetic spectra tailored at the effective temperature obtained via IRFM and absolutely calibrated via $\theta_{\rm IRFM}$ confirms the accuracy of the zero point of our $T_{\rm eff}$ scale in both metal-rich and -poor regime.

3. Insights from 3D models

All IRFM implementations depend on theoretical model atmospheres to estimate the flux outside of the photometric bands as well as for computing infrared monochromatic fluxes (e.g. Casagrande et al. 2006, and Section 2). One might ask if the results presented here will change once large grids of synthetic spectra computed from 3D model atmosphere will become available. To this purpose, we have tested how accurately the effective temperatures of 3D synthetic spectra are recovered via IRFM. A preliminary solar and K dwarf ($T_{\rm eff}$ = 4780 K, [Fe/H] = 0.0) model were used, computed using the radiative transfer code OPTIM3D (Chiavassa et al. 2009). Two models clearly do not cover the entire $T_{\rm eff}$ and [Fe/H] space parameter of dwarfs and subgiants, but they already give interesting insights.

The effective temperature of the solar model is recovered within 10 K, and that of the K dwarf within 20 K. In terms of synthetic colours (Johnson-Cousins, 2MASS and SDSS), the differences between 1D and 3D models are usually within 0.01 magnitudes (even in the H band, where 3D effects are more pronounced), except for the bluest wavelengths (Johnson U and Sloan u) where much higher discrepancies are found. Notice though, for the F, G and K type stars analyzed in this work, very little flux is emitted shortward of the blue band. Also, the calibration procedure via solar twins would naturally cancel the 10 K offset found for the 3D synthetic solar spectrum and reduce by half the offset found for the K dwarf.

Our analysis suggests that 3D effects becomes increasingly important as moving to lower $T_{\rm eff}$, where temperature structure and inhomogeneities affect the formation of molecules. However, for very cool stars we remark that additional physical processes (dust formation) and other technical complications become increasingly important when trying to determine effective temperatures (Casagrande et al. 2008).

4. Conclusions

The IRFM is known to be one of the most precise and model independent ways of determining stellar effective temperatures without resorting on interferometric angular diameters. Until now however, the accuracy of the IRFM was in question, with different implementation returning discordant results; our calibration procedure based on solar twins has improved upon this issue, reducing the uncertainty to only 15 – 20 K.

At this level of accuracy, we can start discussing the effect of using different model atmospheres, in particular 3D synthetic spectra. Obviously the calibration via solar twins prevents from any effect at the solar temperature and metallicity. While more 3D models are clearly needed to explore the entire $T_{\rm eff}$ and [Fe/H] space, the K dwarf suggests that only minor differences are expected for a fairly large space parameter centered around the solar value.

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