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METAL-POOR BENCHMARK STARS AND GAIA

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Abstract. Gaia will deliver stellar properties for up to 1 billion stars. Effective temperatures, surface gravity, and ages are some of the *products* of the coordination unit 8. To properly calibrate Gaia data and the methods that are used, extensive ground-based data has been obtained on sets of *calibration stars*. There are a list of about 40 of the brightest benchmark stars, and here we report on our recent work relating to some nearby metal-poor benchmarks observed using interferometric instruments. We determined their angular diameters and along with distances and bolometric fluxes we obtain their effective temperatures ($T_{\rm eff}$), radii and surface gravity ($\log g$) with very little model-dependence. The $T_{\rm eff}$ can differ a lot from those determined using spectroscopic measurements, and with both $T_{\rm eff}$ and log g pre-determined these stars provide a testbed for stellar atmospheres. Using evolutionary models we then determined their masses and ages. We find that to match the observations we are required to significantly lower the mixing-length parameter α from the usual solar-calibrated value $\alpha_{\odot}$, which brings into question the exploitation of predefined stellar model grids constructed using an $\alpha_{\odot}$. We emphasize the important role of characterising the brightest stars where many independent observations allow us to pinpoint shortcomings in models and methods.

Keywords: metal-poor stars, stellar parameters, interferometry, spectroscopy, Gaia

1 Introduction

Bright metal-poor ([M/H] < 1.0) stars have a valuable role to play for advancing our understanding of different aspects of astrophysics. For one, the atmospheres of metal-poor stars require extra care where non-LTE effects and certain atomic collisions can not be ignored. These affect the determination of absolute chemical abundances (Idiart & Thévenin 2000), and thus have consequences for our understanding of the evolution of the galaxy. Secondly, being some of the oldest stars in our Galaxy, they are tracers of the initial conditions in the Milky Way, and determining their ages constrains the age of the Galaxy independent of cosmological observations. Thirdly, they may be considered *problem stars* where classical stellar evolutionary tracks fail to match their observed positions in the HR diagram (Creevey et al. 2012). As nearby stars they can be measured in many different ways and this allows us to look at the details in the models and thus bring to light the shortcomings. For large-scale ground-based and space-based surveys, bright nearby stars play an important role in calibration, and such is the case for the recently launched Gaia spacecraft.

Gaia (Perryman 2005) is an ESA mission designed to measure distances and kinematics of a sample of 1 billion stars from the Milky Way. It provides a full-sky coverage down to a magnitude of ~ 20. It has astrometric, photometric, spectrophotometric, and spectroscopic[*] capabilities. One of its main deliverables which will serve many different astrophysical communities is a catalogue of precise parallactic and kinematical information for each of the 1 billion stars. These data are processed and will be delivered by coordination units dedicated to these tasks. Within the Gaia consortium the coordination unit 8 (CU8), entitled astrophysical parameters, is

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[*] Radial velocities will be available to magnitude ~ 17.

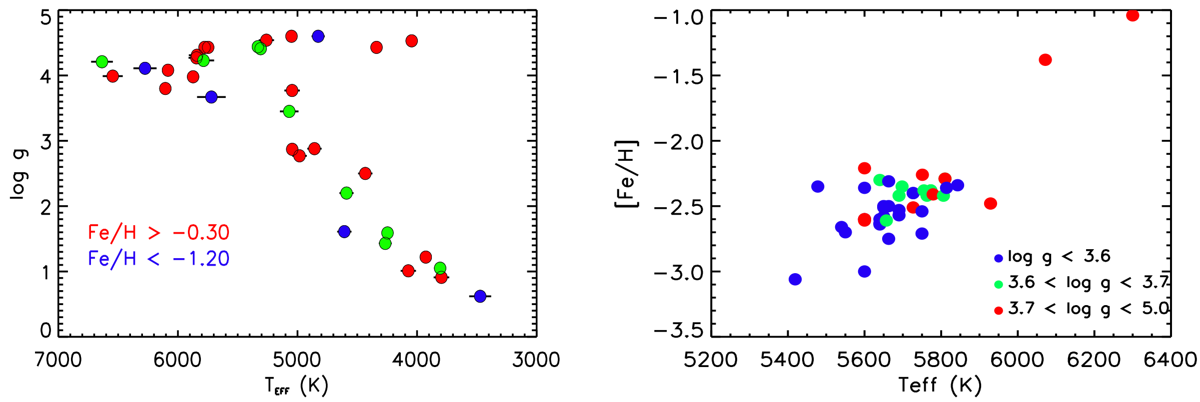

Fig. 1. Left: Gaia benchmark stars. **Right:** Published iron abundances of the metal-poor star HD 140283.

dedicated to extracting fundamental parameters such as $T_{\rm eff}$, $\log g$, metallicities and ages for one billion stars. These parameters are derived primarily by three main packages: GSP_Phot, GSP_Spec, and FLAME. The first two derive atmospheric parameters from the photometry and spectroscopy, respectively, and the latter derives masses and ages. In order to deliver these properties as accurately and as precisely as possible, the analysis tools need to be calibrated with bright nearby stars, ones which, for example, can be measured with interferometry. A list of benchmark stars have been defined by the Stellar Atmospheres Models Group[†] (Heiter et al. in prep., Blanco-Cuaresma et al. 2014; Jofre et al. 2013) and huge efforts and collaborations are underway for obtaining and interpreting data for these stars from ground-based instruments. These stars are shown in Fig. 1 (left), along with various determinations of $T_{\rm eff}$ and [Fe/H] from the literature of HD 140283 (right, Soubiran et al. 2010), illustrating the importance of determining $T_{\rm eff}$ independently of stellar atmospheres. Here we report on our interferometric observations of some bright nearby metal-poor stars.

2 Observations

2.1 *Interferometric observations*

We are conducting an observational interferometric program using the CHARA array. We have obtained observations using the infra-red Classic and visible VEGA interferometers. We extracted visibilities for a total of six metal-poor stars and here we describe our results for a giant HD 122563, a sub-giant HD 140283 and a dwarf HD 103095 (Gmb 1830) (Creevey et al. 2012, 2014). The observations were obtained between the years 2007 and 2014 in two- or three-telescope mode with Classic and VEGA on CHARA. For HD 122563 we also took data from the PTI archive (1999-2002). To determine the angular diameters θ for the stars we fitted visibility functions to the interferometric visibility data. The visibility measurement is a function of the distance between the telescopes (the baseline), the wavelength of observation λ, and the angular diameter of the star (θ). Two examples of the data and fits to a 3D/1D limb-darkened disk function are shown in Fig. 2. These data were obtained with the Classic instrument on CHARA and the Palomar Testbed Interferometer (PTI) (left) and the VEGA instrument on CHARA (right). In Table 1 we give the uniform-disk (UD), 1-D limb-darkened (1D) and 3-D limb-darkened (3D) angular diameters. The 1D diameters were fitted using limb-darkening coefficients from Claret (2000) and Claret et al. (2012). The 3D diameters were obtained using convection simulations (see e.g. Bigot et al. 2011; Chiavassa et al. 2012).

To convert the angular diameter to the fundamental properties, the radius R, effective temperature $T_{\rm eff}$, and surface gravity g, we use the following equations

$$R = \frac{\theta}{\pi}, \qquad T_{\rm eff} = \left(\frac{1}{\sigma_{\rm SB}} \frac{F_{\rm BOL}}{\theta^2} \right)^{0.25}, \qquad g = \frac{GM}{R^2}, \tag{2.1}$$

[†]http://www.astro.uu.se/~ulrike/GaiaSAM/

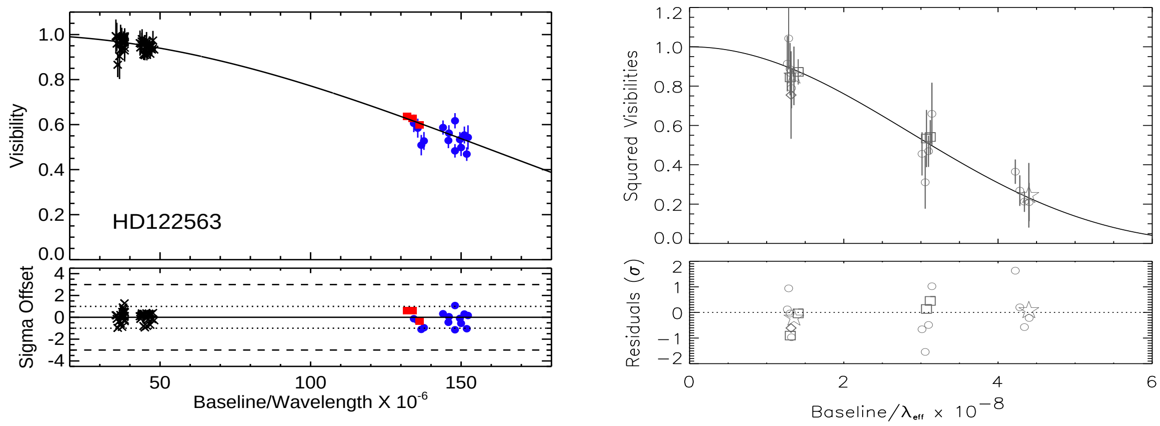

Fig. 2. Fit of visibility data for HD122563 and HD140283 (left/right) to 1D limb-darkened disk function.

Table 1. Angular diameters of three metal-poor stars. Units in milliarcseconds (mas).

	$\theta_{\rm UD}$	$\theta_{\rm 1D}$	$\theta_{\rm 3D}$
HD 122563	0.924 ± 0.011	0.948 ± 0.012	0.940 ± 0.011
HD 140283	0.340 ± 0.012	0.353 ± 0.013	0.353 ± 0.013
HD 103095	0.664 ± 0.015	0.679 ± 0.015	....

where π is the parallax, $F_{\rm BOL}$ is the bolometric flux received at the top of the Earth's atmosphere, $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant, G is the gravitational constant, and M is the stellar mass. These parameters are given in Table 2. M can be estimated from stellar evolution tracks and/or spectral typing and even assuming a conservative precision of 20%, $\log g$ can be derived to 0.1 dex. $F_{\rm bol}$ can be determined using different methods (see below).

2.2 Photometric and astrometric observations

To determine the bolometric flux of the star we need to measure its spectral energy distribution (SED). The SED that we observe, however, is a set of points corresponding to different wavelength regions, e.g. BVRI photometry. Additionally the observed SED can also contain a reddened component from interstellar extinction. The amount of absorption is given by A_V. For our stars we used the classical formula using the observed V magnitude, bolometric corrections along with an assumed A_V, and SED fitting using a compilation of photometry-converted-to-flux measurements. The parallaxes are taken from the Hipparcos catalogue (van Leeuwen 2007) and Bond et al. (2013) for HD 140283.

3 Analysis

3.1 Comparison of Spectroscopic and Interferometric $T_{\rm eff}$

The determination of a spectroscopic $T_{\rm eff}$ is difficult for metal-poor stars due to, for example, deviations from local thermodynamic equilibrium. In Figs. 3 we show a comparison between our interferometrically derived $T_{\rm eff} \pm 1\sigma$ (shaded region) along with spectroscopic determinations of $T_{\rm eff}$ and [Fe/H] taken from the PASTEL catalogue (Soubiran et al. 2010). There is excellent agreement between interferometric and spectroscopic values for HD 122563 and HD 140283 for the most recent spectroscopic determinations. The dashed lines for HD 140283 represent the zero-reddened solution. However, for HD 103095 there is quite a large offset. This could be explained by a systematic error affecting the interferometric observations, or difficulties with model atmospheres for deriving $T_{\rm eff}$ at high $\log g$. Further investigation is needed.

Table 2. Complementary observations and derived parameters for three metal-poor stars.

	HD 122563	HD 140283*	HD 103095
[Fe/H]/Class	–2.5/III	–2.5/IV	–1.4/V
V (mag)	6.19 ± 0.02	7.2 ± 0.01	6.45 ± 0.02
π (mas)	4.22 ± 0.035	17.15 ± 0.14	109.99 ± 0.41
A_V (mag)	0.01 ± 0.01	0.0/0.1 ± 0.04	0.00 ± 0.01
[Z/X$_s$]	–2.3 ± 0.1	–2.1 ± 0.2	–1.3 ± 0.1
θ (mas)	0.940 ± 0.011	0.353 ± 0.013	0.679 ± 0.015
$F_{\rm bol}{}^{\dagger}$	13.16 ± 0.36	3.89/4.22 ± 0.066/0.067	8.27 ± 0.08
R (R$_\odot$)	23.9 ± 1.9	2.21± 0.08	0.664± 0.015
$T_{\rm eff}$ (K)	4585 ± 43	5534/5647 ± 103/105	4818 ± 54
L (L$_\odot$)	232 ± 6	4.12/4.47 ± 0.10	0.213 ± 0.002
$\log g$	1.57 ± 0.06	3.65 ± 0.06	4.57 ± 0.07
M (M$_\odot$)	0.855 ± 0.025	0.780/0.805 ± 0.010	0.635 ± 0.025
t (Gyr)	$12.6^{+1.1}_{-1.6}$	13.7/12.2 ± 0.7/0.6	$12.1^{2.0}_{-2.2}$
$\log g_{\rm model}$	1.60 ± 0.04	3.64/3.65 ± 0.03/0.02	4.60 ± 0.02
α	1.31 ± 0.10	1.0 ± 0.3	0.68 ± 0.10
Y_i	0.245 ± 0.015	0.245	0.235 ± 0.025

*Two solutions are given based on different interstellar absorption values A_V. †Units of $F_{\rm bol}$ are 1e-8 × erg s^{-1} cm^{-2}.

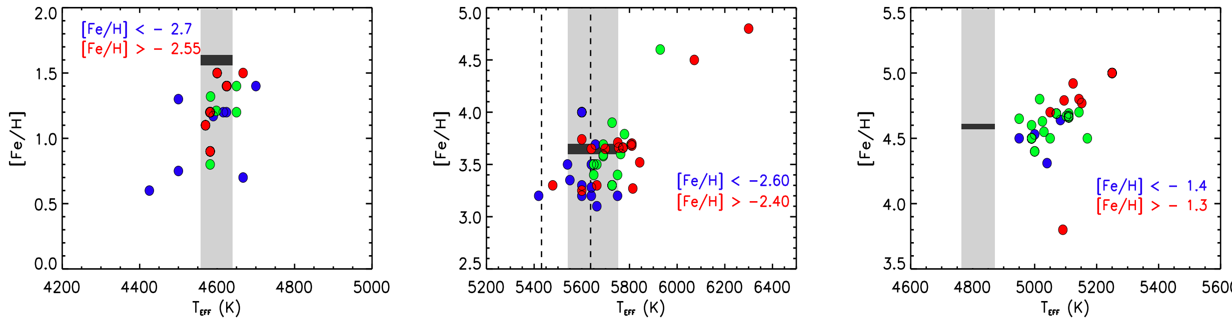

Fig. 3. Comparison of $T_{\rm eff}$ from the literature and interferometry (shaded) for HD 122563, HD 140283, HD 103095 (L–R).

3.2 Interpretation of observations with models

We used the CESAM2K stellar evolution code (Morel 1997; Morel & Lebreton 2008) to derive the mass M and the age t of the three stars. This was done by fitting L, $T_{\rm eff}$ and the metallicity [M/H] to fine-tuned stellar evolution tracks. For the dwarf and sub-giant star we included elemental diffusion in the models to help explain the observed surface metallicity and to better estimate the stellar age. In order to match the observations it was necessary to significantly reduce the value of the mixing-length parameter α from that of the Sun. With an assumption on either the mixing-length parameter or the initial helium abundance of the star, the other can be determined along with the mass and the star's age. These stellar parameters are given in the lower part of Table 2.

4 Conclusions

Interferometry allows the direct measure of stellar observables, and when combined with the distance and $F_{\rm bol}$, R, $T_{\rm eff}$, L and $\log g$ can be determined with none or very little model-dependence. For metal-poor stars, the determination of $T_{\rm eff}$ independent of stellar atmospheres provides critical tests of the models. Gaia will deliver atmospheric properties along with masses and ages of up to 1 billion stars. Independent determinations of these properties for several benchmark stars serve as important calibration measures of the Gaia pipelines GSP_Phot, GSP_Spec (atmospheric properties) and FLAME (luminosities, masses, ages).

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