



Gaia FGK benchmark stars and their reference parameters

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Abstract. In this article we summarise on-going work on the so-called Gaia FGK Benchmark Stars. This work consists of the determination of their atmospheric parameters and of the construction of a high-resolution spectral library. The definition of such a set of reference stars has become crucial in the current era of large spectroscopic surveys. Only with homogeneous and well documented stellar parameters can one exploit these surveys consistently and understand the structure and history of the Milky Way and therefore other of galaxies in the Universe.

Keywords : Milky Way structure - calibration of stellar parameters - reference libraries

1. Introduction

Stellar spectral libraries are commonly needed for two immediate purposes: (1) to build population synthesis models, which help us to understand the structure and evolution of galaxies; (2) to evaluate methods to determine stellar atmospheric parameters, which help us to understand the structure and evolution of stars and thus the Milky Way. Spectral libraries can be built from observations or from theoretical models. Hence, for a thorough comprehension of stellar spectra, accurate atomic and molecular data as well as atmospheric models are necessary. Additionally good quality observations are required to validate the modelled spectra.

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The Sun has been so far the (benchmark) star most widely used to calibrate and evaluate analyses of stellar spectra. The Sun represents, however, only a fraction of spectral-types (G-type) of stars in our Galaxy. To understand how to develop atmospheric models, parametrisation pipelines of stellar spectroscopic surveys, and therefore proper stellar spectral libraries, we need more benchmark stars representing FGK stars of various metallicities which are so important for galactic studies.

Our aim is to define such a set of benchmark stars and provide homogeneous parameters for them whose determination is well documented. These stars have been chosen several years ago to be the pillars of the calibration of the parameters that will be derived for one billion stars by Gaia. Observations on the NARVAL instrument in France and HARPS instrument in Chile have been conducted in the past years for that purpose. We encourage to use these stars as part of any strategy to calibrate, evaluate, and homogenise different methods and databases, such as the Gaia-ESO Survey (Gilmore et al. 2012) is doing with its current ~ 15000 observations. This work on the Gaia Benchmark Stars will be fully described in three different articles. The first one (Heiter et al. 2013, Paper I) explains the selection criteria of Benchmark Stars and the determination of the effective temperature (T_{eff}) and surface gravity ($\log g$). The second one (Blanco-Cuaresma et al. 2013, Paper II) introduces our spectral libraries of Benchmark Stars. The third one (Jofré et al. 2013, Paper III) consists of a detailed spectral analysis of this library in order to define a metallicity scale ($[\text{Fe}/\text{H}]$) for these stars.

Here we present a summary of this work, we also discuss the implications of the uncertainties and finally we give a general comparison of our parameters to previous parameters found in the literature.

2. Determination of Atmospheric Parameters

The key aspect of the Gaia Benchmark Stars is that the stellar parameters T_{eff} and $\log g$ are determined using fundamental relations, that means, independently from the spectra. For a star to be one of our benchmarks, we need to know, a priori, its radius, its bolometric flux and its distance. Additionally, it must be bright enough to obtain very high signal-to-noise and high resolution spectra. Our first set of stars consists of 34 Hipparcos stars and covers a wide range of stellar parameters. The list of stars with their basic properties, together with their atmospheric parameters is in Table 1.

2.1 Effective temperature

The effective temperature is determined from the Stefan-Boltzmann relation

$$F_{\text{bol}} = \sigma(0.5\theta_{\text{LD}})^2 T_{\text{eff}}^4 \quad (1)$$

where F_{bol} is the bolometric flux, θ_{LD} is the angular diameter of the star, and σ is the Stefan-Boltzmann constant. About 70% of the stars have a direct measurement of their radius via interferometry, while the rest has radii using calibrations, such as infrared spectrophotometry and photometric surface-brightness relations. The bolometric flux is also determined only for half of the stars directly from the integration of the flux over the whole spectrum. For the rest, photometric relations are used. Uncertainties of the angular diameter and the bolometric flux are taken into account in the error of the temperature.

2.2 Surface Gravity

The surface gravity is determined by the Newton's law of gravity

$$g = \frac{GM}{(0.5\theta_{\text{LD}}/\pi)^2} \quad (2)$$

where G is the gravitational constant and M and π are the mass and parallax of the star, respectively. To determine the mass, we considered stellar evolution models using the luminosity derived from the bolometric flux and the parallax, the direct effective temperature and initially a metallicity value from the literature. If our estimated metallicity (see below) is significantly different from the chosen literature value, we re-estimated $\log g$ using our own result. We used different evolutionary tracks to estimate an error for the mass. Uncertainties in the angular diameter, the mass and the parallax are taken into account for the error in $\log g$. More details about the direct stellar parameter measurements will be found in the forthcoming Paper I.

2.3 Metallicity

The metallicity was determined by analysing Fe I and Fe II lines in high resolution ($R = 70000$) and high signal-to-noise spectra. Iron abundances were estimated by fixing T_{eff} and $\log g$ to their fundamental values. Up to seven different methods¹ were considered for this analysis, which used equivalent width measurements, such as those from DAOSPEC (Stetson & Pancino 2008) and ARES (Sousa et al. 2007) to determine abundances with codes like MOOG (Sneden 1973) and GALA (Mucciarelli et al. 2013). Additional methods based on synthetic spectra like SME (Valenti & Piskunov 1996), MATISSE (Recio-Blanco et al. 2006) and Turbospectrum (Plez 2012) were employed.

Each method considered the same 1D-LTE MARCS atmospheric models (Gustafsson et al. 2008) and line list created for the Gaia-ESO Survey (Heiter et al. 2014, in

¹ All methods have been adapted from those used to analyse the UVES targets of the Gaia-ESO Survey.

prep). In addition, they used the same value for rotational velocity (taken from the literature), but micro- and macro-turbulent velocities were determined simultaneously with $[\text{Fe}/\text{H}]$. Finally, each group analysed the same spectra, which are part of the spectral libraries of Benchmark Stars (see Sect. 3) and cover the wavelength range from 480 to 680 nm.

The final result of $[\text{Fe}/\text{H}]$ was obtained by combining the abundances obtained for each iron line individually. We considered the values of only those lines where at least three methods obtained an abundance that agreed within 2σ with the mean abundance. In addition, NLTE corrections were applied for each line individually using the corrections of Lind et al. (2012). Finally, the $[\text{Fe}/\text{H}]$ was calculated from the mean of the selected lines relative to the solar abundance value of Grevesse et al. (2007).

We have given special importance in quantifying some of the many different sources of errors that affect the metallicity. Among them we have quantified: (i) the intrinsic scatter of the line-to-line analysis; (ii) the difference obtained in the metallicity after considering the errors associated to T_{eff} , $\log g$ and v_{mic} ²; (iii) the difference obtained from ionised and neutral iron abundances; (iv) the difference obtained from neutral iron abundances under LTE and NLTE. Details of this analysis can be found in Paper III.

3. Spectral library

Since the Gaia Benchmark Stars are located in both hemispheres, not all of them are observed with the same instrument. For that reason, the spectra of the Gaia Benchmark Stars have different properties such as resolution, wavelength coverage and flux calibrations. The first version of our library includes a collection of spectra from three instruments: NARVAL in France and UVES and HARPS in Chile.

In order to use the Benchmark Stars as calibrators for a given data set, our spectra must be adapted to the resolution, wavelength range and sampling of these data. We have developed a software for this purpose which is also presented in this proceeding by Blanco-Cuaresma et al. (2013). As an application of this software, we transformed our original observations to look like UVES data for the Gaia-ESO survey, meaning that we resampled and convolved them to the FLAMES-UVES resolution and selected the desired wavelength range. We also determined the radial velocity and shifted the spectra to rest frame. For the metallicity determination, from the high resolution spectra of our library, we created a data set like FLAMES-UVES spectrum, but with higher resolution. With our program we are able to edit the format of the original archive spectra and create spectral libraries with any desired spectral resolution and

²This is done by determining the metallicity by fixing T_{eff} , $\log g$ and v_{mic} considering their associated uncertainties.

wavelength coverage (within the limits of the original spectra). A full documentation on the original spectra and how our tools work is found in Paper II³.

4. Results

A comparison of our parameters with the literature can be seen in Fig. 1. The literature value is the averaged one of all references found in the PASTEL catalogue (Soubiran et al. 2010) between the years 2000 and 2012 and the standard deviation of the mean is plotted as black error bars in the figure. We show the difference between our values and the values from the literature for the effective temperature, surface gravity and metallicity with red squares in three different panels. The red error bars correspond to the mean absolute error in our parameters.

The large scatter found in the literature reflects the significant differences of the spectroscopic methods. An important result of our work is that we provide homogeneous atmospheric parameters obtained by one method, and where T_{eff} and $\log g$ are determined independently of spectroscopy.

One can see that some of our values differ significantly from the mean literature ones. Some extreme cases are HD220009, Gmb 1830 and γ Sge, whose direct effective temperatures are very different to the spectroscopic or photometric ones. At variance, the various measurements for the Sun agree very well, but this may reflect the fact that methods are usually calibrated on this star. One important reason for the differences seen between the parameters of our work and the literature, is that the common way to determine parameters from the spectra are very model dependent. These models are imperfect. For some cases, the stellar parameters can change significantly with respect to those determined independently from the spectrum.

Table 1 shows the parameters for T_{eff} , $\log g$ and $[\text{Fe}/\text{H}]$ taking into account the errors mentioned in Sect. 2. Since we are actively working on defining a consistent and well established set of parameters and associated errors, the values listed in Table 1 are approximative. The final values can be found in the corresponding Paper I and III.

5. Conclusions

We presented a summary of on-going work on FGK Gaia Benchmark Stars by providing their basic information such as coordinates, magnitudes and stellar parameter ranges in Table 1. In addition, we can provide observed spectral libraries that can simulate different data sets. The Gaia-ESO Survey is currently using this small, but

³Additional material on the library can be found in the public ftp directory <ftp://ftp.obs.u-bordeaux1.fr/pub/jofre/Libraries/Benchmark4GES/>

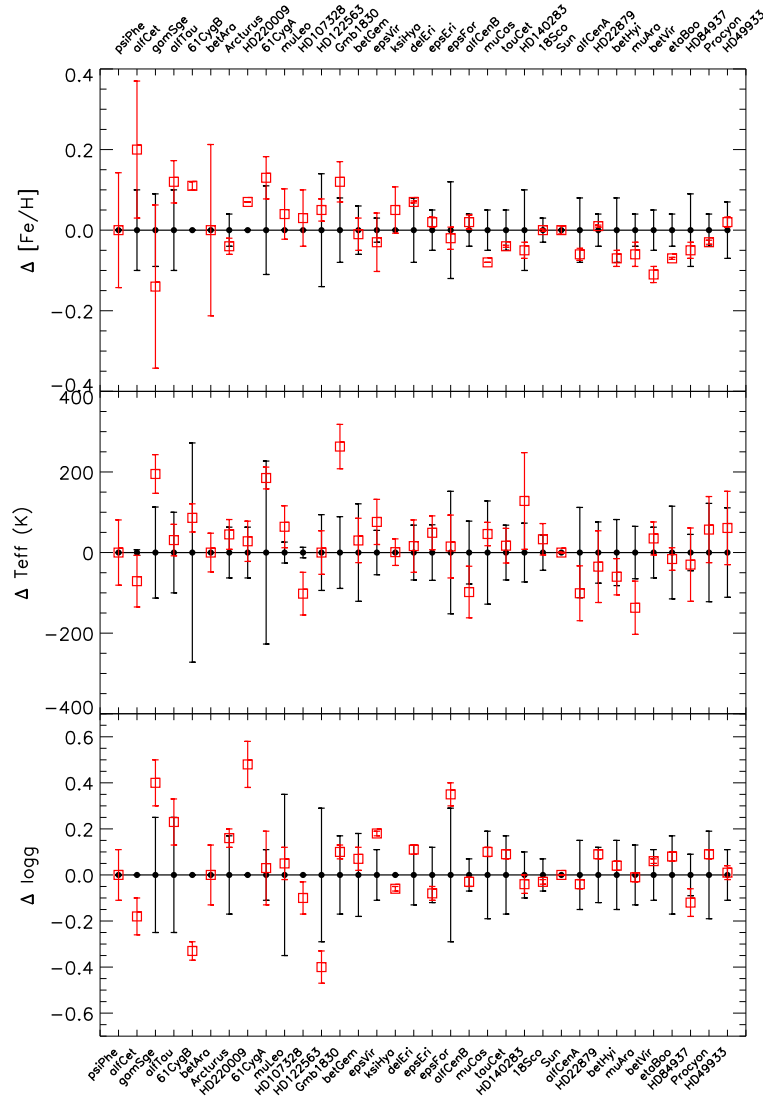


Figure 1. Comparison of our parameters with previous works reported between the years 2000 and 2012 in the literature as retrieved from PASTEL (Soubiran et al. 2010). Black error bars indicate the standard deviation in the results of parameters from the literature. Red error bars indicate the mean absolute error of our results (see text). The squares represent the difference between our atmospheric parameters and the average of the literature parameters from PASTEL.

representative sample of FGK reference stars to test the different methods and homogenise their results, showing already advantages of having more well established pillars than the Sun. Because T_{eff} and $\log g$ are independent of the spectra, we en-

Table 1. General information and atmospheric parameters of the Gaia FGK Benchmark Stars. The first three columns indicate the name of the star and its coordinates. The fourth column lists the spectral type, while the fifth one denotes the V magnitude. The last three columns indicate the temperature, surface gravity and metallicity range, respectively.

star	RA	DEC	spec. type	V	T _{eff} (K)	log <i>g</i>	[Fe/H]
F dwarfs							
Procyon	07 39 18.119	+05 13 29.96	F5IV-V	0.4	6550±80	3.99± 0.02	+0.01± 0.03
HD 49933	06 50 49.832	-00 32 27.17	sdF5	8.3	6640±90	4.21± 0.03	-0.41± 0.02
HD 84937	09 48 56.098	+13 44 39.32	F2V	5.8	6360±90	4.11± 0.06	-2.03± 0.04
FGK subgiants							
δ Eri	03 43 14.901	-09 45 48.21	K1III-IV	3.5	5050±70	3.77± 0.02	+0.06± 0.01
HD 140283	15 43 03.097	-10 56 00.60	sdF3	7.2	5610±120	3.67± 0.04	-2.36± 0.04
ε For	03 01 37.637	-28 05 29.60	K2VF	5.93	5120±80	3.45± 0.05	-0.60± 0.04
η Boo	13 54 41.079	+18 23 51.79	G0IV	2.7	6110±30	3.80± 0.02	+0.32± 0.02
β Hyi	00 25 45.070	-77 15 15.29	G0V	2.8	5870±50	3.98± 0.02	-0.04± 0.03
Solar-type stars							
α CenA	14 39 36.494	-60 50 02.37	G2V	0.1	5850±70	4.31± 0.02	+0.26± 0.03
HD 22879	03 40 22.064	-03 13 01.12	F9V	6.7	5870±90	4.23± 0.02	-0.86± 0.01
Sun	—	—	G2V	-26.8	5777	4.44	+0.01± 0.01
μ Cas	01 08 16.395	+54 55 13.23	G5Vb	5.2	5310±30	4.41± 0.02	-0.81± 0.01
τ Cet	01 44 04.083	-15 56 14.93	G8.5V	3.5	5330±40	4.44± 0.02	-0.49± 0.02
α CenB	14 39 35.063	-60 50 15.10	K1V	1.4	5260±60	4.54± 0.02	+0.22± 0.02
18 Sco	16 15 37.269	-08 22 09.99	G2Va	5.5	5750±40	4.43± 0.01	+0.03± 0.01
μ Ara	17 44 08.701	-51 50 02.59	G3IV-V	5.1	5900±70	4.27± 0.02	+0.35± 0.04
β Vir	11 50 41.718	+01 45 52.99	F9V	3.6	6080±40	4.08± 0.01	+0.24± 0.03
Red Giants							
Arcturus	14 15 39.672	+19 10 56.67	K1.5III	-0.1	4250±40	1.59± 0.04	-0.52± 0.04
HD 122563	14 02 31.845	+09 41 09.95	F8IV	6.2	4590±50	1.61± 0.07	-2.64± 0.08
μ Leo	09 52 45.817	+26 00 25.03	K2III	3.9	4470±50	2.50± 0.07	+0.25± 0.07
β Gem	07 45 18.950	+28 01 34.32	K0IIIb	1.1	4860±60	2.88± 0.05	+0.13± 0.09
ε Vir	13 02 10.598	+10 57 32.94	G8III	2.8	4980±60	2.77± 0.01	+0.15± 0.08
ξ Hya	11 33 00.115	-31 51 27.44	G7III	3.5	5040±30	2.87± 0.01	+0.16± 0.11
α Tau	04 35 55.239	+16 30 33.49	K5III	0.9	3930±40	1.22± 0.10	-0.37± 0.56
ψ Phe	01 53 38.741	-46 18 09.60	M4III	4.4	3470±80	0.62± 0.11	-1.24± 0.14
γ Sge	19 58 45.429	+19 29 31.73	M0III	3.5	3810±50	1.05± 0.10	-0.17± 0.20
α Cet	03 02 16.773	+04 05 23.06	M1.5IIIa	2.5	3800±60	0.91± 0.08	-0.45± 0.17
β Ara	17 25 17.988	-55 31 47.59	K3Ib-II	2.8	4170±50	1.01± 0.13	-0.05± 0.21
HD 220009	23 20 20.583	+05 22 52.70	K2III	5.0	4280±50	1.43± 0.10	-0.74± 0.06
HD 107328	12 20 20.981	+03 18 45.26	K0IIIb	5.0	4500±50	2.11± 0.07	-0.33± 0.07
K dwarfs							
ε Eri	03 32 55.845	-09 27 29.73	K2Vk	3.7	5050±40	4.60± 0.03	-0.09± 0.02
Gmb 1830	11 52 58.769	+37 43 07.23	G8Vp	6.5	4830±60	4.60± 0.03	-1.46± 0.05
61 Cyg A	21 06 53.952	+38 44 57.99	K5V	5.2	4340±30	4.43± 0.16	-0.33± 0.05
61 Cyg B	21 06 55.264	+38 44 31.40	K7V	6.0	4050±40	4.53± 0.04	-0.38± 0.03

courage colleagues working on other spectroscopic surveys to calibrate and link their pipelines with the current Gaia-ESO ones using the Gaia Benchmark Stars as well.

The Gaia Benchmark Stars will be used as a pillar for calibrations of Gaia and other spectroscopic surveys, therefore it is of extreme importance to have a well defined set of atmospheric parameters. As commented above, spectroscopic and fun-

damental parameters can differ significantly for some stars. This reminds us of the importance of having standard set of stars with stellar parameters that are independent from spectroscopy, as this helps to make improvements to spectroscopic methods and models for different kinds of spectral-type stars.

Although our metallicities are scaled to the Gaia-ESO material, such as line list, atmospheric models and wavelength range, we look forward to improve our values in a way that it is consistent with methods outside Gaia-ESO. The connection between surveys is crucial to have consistent parameters to understand the history of the Milky Way.

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