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Gaia FGK benchmark stars: a bridge between spectroscopic surveys

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Abstract. The *Gaia* benchmark stars (GBS) are very bright stars of different late spectral types, luminosities and metallicities. They are well-known in the Galactic archaeology community because they are widely used to calibrate and validate the automatic pipelines delivering parameters of on-going and future spectroscopic surveys. The sample provides us with consistent fundamental parameters as well as a library of high-resolution and high signal-to-noise spectra. Since the SSL community can thus study details of high-resolution spectroscopy and compare results between different survey pipelines, the GBS is therefore very central to that community. We discuss some results arising from using the GBS as the main data source for spectral analyses.

Keywords : stellar atmospheres – Gaia – spectroscopic surveys

1. Introduction

One goal of the Galactic archaeology community is to unravel the structure and evolution of the Galaxy. This is approached by studies of the spacial, dynamical and chemical distributions of stars of different ages at different Galactic directions, based on the photometry, astrometry, spectroscopy and seismology of large samples of stars complemented by distances, proper motions, radial velocities, fundamental stellar parameters and individual chemical abundances.

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In the era of ultra-high precision stellar astrophysics opened up by the *CoRoT*, *Kepler*, and *Gaia* missions, there are many spectroscopic surveys available to the community today. Notable examples are RAVE, SDSS, LAMOST, Gaia-ESO, APOGEE and GALAH. In the future, high-resolution spectroscopic surveys like WEAVE and 4MOST dedicated to follow up Gaia sources will provide even larger datasets. These different surveys are designed to observe different kinds of stars, and therefore their spectra are of a different nature. Some cover the optical wavelength range, others cover the infrared. Some target the nearby solar neighbourhood, others the faint distant halo. The resolution, signal-to-noise, and wavelength coverage, also vary from one survey data to another. This naturally leads to different and independent automatic pipelines developed for each of these surveys. Some of the pipelines estimate parameters by spectrum synthesis, others use equivalent width measurements.

The ideal way to compare the results of these pipelines, which gives a handle of the systematic uncertainties of these results, is to test the pipelines against sets of reference stars *in common*. The GBS is one example of a very suitable and successful set of common stars. Other examples are stars in well-known clusters like M67, and in fields with asteroseismic observations (see e.g. Pancino et al. 2017)

At the IWSSL 2017 workshop, several issues of stellar spectroscopy that have arisen from the analysis of GBS were discussed in the context of large spectroscopic surveys, Gaia and the future of Galactic archaeology. We start with a short description of the GBS, then we summarise two of our recent activities and we finalise with future prospects.

2. The FGK Gaia Benchmark stars

The GBS are among the main calibrators of the Gaia-ESO Survey, and are a central source for validation of many recent independent spectroscopic analysis. Documentation of the work can be found in the series of six A&A articles published between 2014 and 2017. In these articles one finds their selection criteria (Heiter et al. 2015), a public spectral library (Blanco-Cuaresma et al. 2014), their spectral analyses for metallicity (Jofré et al. 2014) and α elements and iron-peak abundances (Jofré et al. 2015). Five new metal-poor candidates were added to the GBS list of Hawkins et al. (2016), and recently a study of the systematic uncertainties in abundance determinations was presented by Jofré et al. (2017).

The final sample with its recommended parameters is available in the website of our library (`https://www.blancocuaresma.com/s/benchmarkstars`).

3. Validation/calibration fields for spectroscopic surveys

Recently, having large numbers of targets in common to different spectroscopic surveys has become one of the first priorities as it allows one to perform direct comparisons of the different pipelines. This is necessary both for improving the performance of the pipelines and also for developing a strategy to place the parameters of the different surveys onto the same scale. Furthermore, the larger the sample of stars, the better for developing data-driven methods to transfer the information (e.g. stellar parameters and chemical abundances) from one dataset onto another. However, so far the number of stars in common between surveys that are publicly available to the community is still limited.

In July 2016 a group of specialists involved in the development of a pipeline for parameterising survey spectra held a workshop entitled "Industrial Revolution of Galactic Astronomy" and organised in Sexten by A. Miglio, P. Jofré, L. Casagrande and D. Kawata. During a week the group compared and discussed the parameters and abundances obtained by different survey pipelines. There are about 200 stars in common between Gaia-ESO Data Release 4 and APOGEE Data Release 13 whose parameters can be obtained from public databases[1]. These common stars correspond to a subset of GBS, cluster members and CoRoT targets. A comparison of their parameters is shown in Fig. 1, where each symbol represents a different set of stars. At the top left of each panel the mean difference is indicated, with its standard deviation in parenthesis.

Temperature, surface gravity and metallicity show a very good agreement, with negligible systematic differences and a scatter that is comparable with errors typical of such parameters. This is encouraging, since both pipelines have been developed in completely independent ways, employing very different strategies and focused in different spectral windows with no overlap. The APOGEE pipeline estimates the best parameters by χ^2-optimisation with a grid of synthetic spectra in the infrared (see García Pérez et al. 2016). In contrast, the GES parameters and abundances are the product of the homogenisation of multiple independent pipelines, which employ a variety of approaches, including estimates of excitation and ionisation equilibria based both on equivalent widths and on χ^2-optimisation of synthetic spectra in the optical (Smiljanic et al. 2014, Hourihanne et al., in prep). The α abundances, however, do not show a clear correlation like the other parameters do, and required further investigation.

It is important to clarify that the [α/Fe] values reported by GES and APOGEE correspond to the value adopted in the atmosphere model that reproduces the synthetic spectrum that best fits the data. However, the value is based on the $\alpha-$element

[1] `http://www.eso.org/qi/` and `http://www.sdss.org/dr13/irspec/` for GES and APOGEE, respectively.

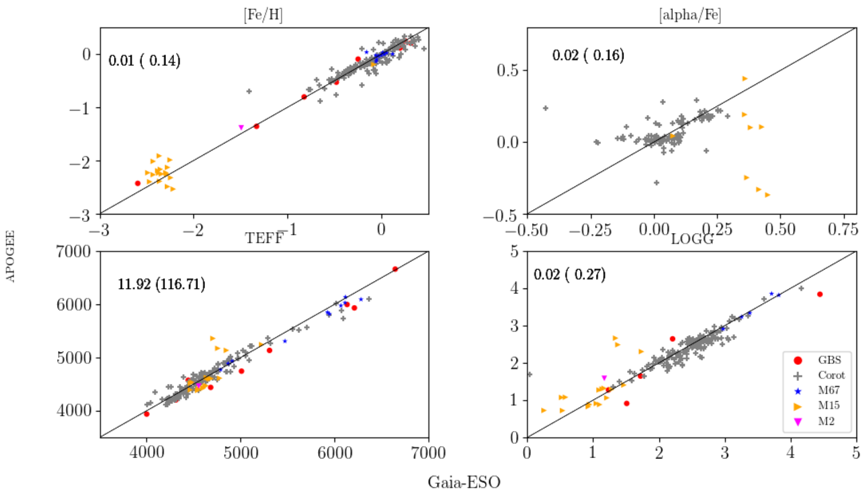

Figure 1. Comparison of stellar parameters of common stars observed by APOGEE and GES.

features dominating the respective spectral regions of the two surveys. For instance, the APOGEE spectra have numerous very strong oxygen features, while the GES spectra are dominated by Mg and Ca features. Since the α elements are produced by slightly different nucleosynthesis processes, it is not surprising if stars have slightly different abundances of, for example, O and Mg. The fact that the [α/Fe] parameters of APOGEE and GES are not tightly correlated does not mean that one of the datasets has incorrect values, but reflects different α signatures in the different spectral domains. Figure 2 shows a comparison of individual α-elements that have been measured by GES and APOGEE for the same stars as shown in Fig. 1. Some of the extreme outliers seen in Fig. 1 are now removed. The correlation improves further when the abundances are weighted according to the precision with which they are measured (right hand panel).

It remains to be seen which is the best way for spectroscopic surveys to yield an α abundance parameter such that different stellar populations can be properly identified, and different surveys properly scaled. This test demonstrates the importance of making clear what the α parameter means for each of the surveys.

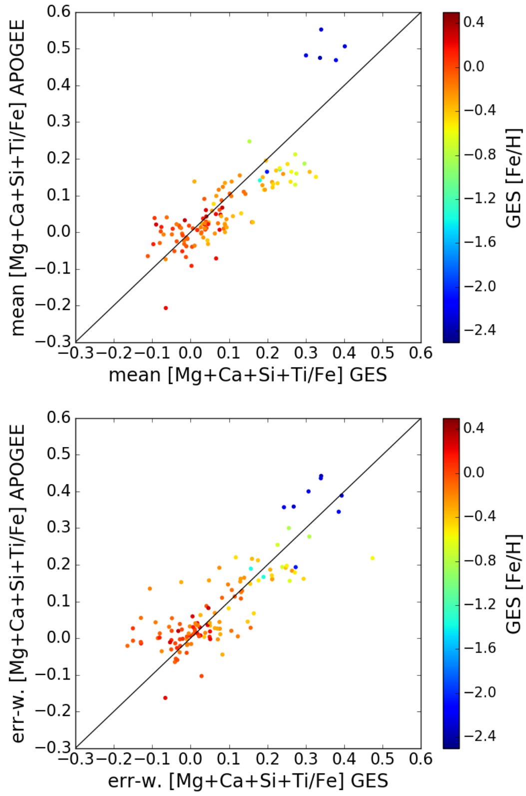

Figure 2. Comparison of α abundances between AGOGEE and GES.

4. The art of stellar spectroscopy

It has been argued that modern astrophysics started with the advent of stellar spectroscopy in the 19th century (Becker 1993)[2]. A remarkable example of stellar spectroscopy is the creation of the Henry Draper (HD) Catalogue, in which the *Harvard Computers* (women hired to perform computations in Harvard) classified by eye more than 200,000 stellar spectra according to the depth of selected lines and leading to the sequence of spectral types we employ today. While the classification scheme used today is basically the same, the amount and quality of data has recently grown massively. The level of detail with which we can now resolve spectral lines with current high-resolution spectrographs is impressive. At the same time, our computers (now machines performing computations) are capable of solving quite complicated equations of stellar structure, including 3D modelling of atmospheres, rotation and

[2]`http://faculty.humanities.uci.edu/bjbecker/huggins/`

departures from local thermodynamic equilibrium. We can thus achieve much higher precision and much more objective classification of stars than was reached simply by eye. However, it has also become evident that even in modern times there is much room for improvement in the art of interpreting stellar spectra. It has been shown that different input material, namely atmosphere models, atomic and molecular data, and observed spectra having different resolutions, wavelength coverage and signal-to-noise ratios (SNR) might give rise to different results in the derived stellar parameters, in particular for metallicity and individual abundances. By fixing those variables, one might be able to quantify the systematic uncertainties in stellar parameters when different methodologies are based on the same input material.

The Gaia-ESO Survey is the first and only project that has attempted, massively and systematically, to employ multiple available techniques on a very large dataset. Its approach has been to combine the results of about 20 different groups analysing simultaneously several thousands of spectra in about 5 different wavelength regions and resolutions. A final value and a statistical uncertainty for the stellar parameters of each star are provided (see talk of R. Smiljanic in this conference (page 83). To the surprise of many, this uncertainty has turned out to be much larger than expected in some cases.

Is it only the different choices of spectral lines and the possibly insufficient SNR of the observations which are to blame for the discrepancies in derived stellar parameters? That is one of the questions we try to answer using the GBS, for which we have spectra at exquisite SNR, resolution and wavelength coverage. In February 2016 a workshop in Cambridge was organised to tackle this question; the results were published by Jofré et al. (2017). We could quantify the differences obtained in abundance determination with different methods based on the same spectral lines, atmosphere models, stellar parameters and atomic data. The methods considered used state-of-the art tools based on synthesis and equivalent-width measurements. Essentially we investigated to what extent the “default" parameters of each method (continuum placement, model interpolation, continuum opacities, etc.) affect the final abundances. We found that differences in continuum normalisation, even in very high SNR spectra, caused an impact of up to 0.6 dex in the retrieved abundances, while weak blends or interpolation of model atmospheres had insignificant effects on final abundances.

5. Future prospects

The GBS work is continuing to progress towards different directions simultaneously. Below we list some of them.

- **Hunting new and better candidates**. Several current interferometric programmes are enlarging the sample of stars with a view to improve the accuracy of measured angular diameters. With Gaia DR2 parallaxes and the new interferometric data, we will revise our GBS sample and provide a new set of stellar parameters.

- **Improving spectral library and line lists for analyses**. We have included spectra of the entire optical range using all setups of archived UVES data. They have been distributed to a small group of people to carry out abundance analyses (see below), and will be provided soon in our Library webpage.
- **Determination of abundances**. We are analysing the new GBS library with the goal of providing reference abundances of light elements (Li, C, N, O, Al, Na) and heavy elements (tbd). For that purpose, extensive work is being undertaken to improve the atomic line list outside the GES range, starting with the entries in the VALD database[3]. Furthermore, significant effort has been invested to select the best wavelength ranges for determining abundances of C, N and O from molecular bands.

The future of Galactic archaeology is moving towards analyses of very large combined datasets provided by future surveys in combination with parallaxes, proper motions and radial velocities (Gaia), colours (LSST), stellar parameters and chemical abundances (4MOST and WEAVE), and masses and ages (K2 and PLATO). At the same time, the extremely high levels of details that we can detect in high-quality spectra of stars in the solar neighbourhood tell us how complex a star like the Sun or Arcturus can be, challenging the finest physical assumptions involved in the theory of stellar structure and evolution. As urged during this conference by E. Griffin, a proper connection between the “wide sweeper" and the “ultimate refiner" is now more important than ever.

6. Acknowledgements

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