Atmospheric parameters of stars in the South Ecliptic Pole Catalogue

prepared by:	P. Jofré, C. Soubiran, Y. Frémat, M. Altmann, S. Blanco-Cuaresma, S. Boudreault, N. Brouillet, T. Cantat-Gaudin,U. Heiter, G. Jasniewicz, T. Nordlander, E. Pancino, G. Seabroke, R. Sordo, F. Thevenin, A. Vallenari
affiliation :	Institute of Astronomy, Cambridge (IoA)

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Abstract

This TN describes the current analysis of stars observed with FLAMES-VLT at the South Ecliptic Pole. The analysis provides stellar atmospheric parameters which can be used for reference for CU8 validations .

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Contents

1 Introduction

The Gaia Ecliptic-Pole Catalogue (GEPC, Altmann, MA-015) is a deep photometric catalogue, included in the IGSL, covering about one square degree around each Ecliptic Pole (EP), built to serve as reference field for the commissioning phase. The main purpose was to test and validate Gaia operations in the very first phase of operations when Gaia's scanning law was focused on the Ecliptic poles. The objects close to the EPs have many Gaia observations already available which are currently used to test the CU pipelines. It is thus crucial to know as well as possible the properties of the objects in those fields to better understand how the DPAC algorithms behave. The GBOG WG submitted a proposal on VLT-FLAMES to characterise the brightest stars of the SEP field ($V < 17$ mag), providing to CU6 and CU8 a sample of about 800 stars with known radial velocities (RVs) and atmospheric parameters (APs). This note aims to report the on-going work on the APs of a subsample of about 100 SEP stars, while the RV part is described in a A&A paper in preparation (Frémat et al.). Our activities related to this work were also presented in the general public German Magazine "Sterne & Weltraum" in April 2014.

2 Spectroscopic data

2.1 The SEP sample

The spectra come from the VLT-FLAMES instrument and were observed as part of the GBOG programme under three ESO proposals between 2010 and 2012 (P.I. Altman, ID: 088.D-0305, 086.D-0295, 084.D-0427). The SEP field includes nearly 450000 stars, the faintest ones being dominated by the Large Magellanic Cloud (LMC) population. Stars brighter than $R = 17$ mag have been randomly selected in order to avoid any bias[1]. These stars have spectra, which are indicated with red circles in the color-magnitude of the EPC in Fig. 1. Stars were observed with GIRAFFE with the setups LR02 and HR21 and with the UVES setup RED-CD#4. A total of 746 GIRAFFE targets (2189 HR21, 1802 LR2 spectra), and 69 UVES targets (211 spectra) are included in the sample, but 22 were rejected because of a too low signal to noise ratio. To assess biases in the determination of parameters and RV, many stars have been observed with all setups. Furthermore, many stars have been observed in different periods, to assess the issue of binarity from RV variations.

The determination of RVs has been coordinated by Y. Frémat and is explained in detail in Frémat et al. (A&A, in prep). In summary, three different methods were employed to determine the RV of each object at each epoch. The methods consist of (1) applying the XCOR.D procedure that optimises the cross-correlation of the observed spectrum with a grid of synthetic spectra, (2) cross-correlation of spectral line centres found in the spectrum with a list of laboratory wave-

[1]Because of the selection of bright stars, it is worth to comment that the sample is biased towards giants, especially in the LMC stars

lengths with the code DAOSPEC (Stetson & Pancino, 2008) and (3) cross-correlation with a mask using the code iSpec (Blanco-Cuaresma et al., 2014a). The results were compared and calibrated with a set of telluric standards and the Gaia radial-velocity standards (Soubiran et al., 2013). The XCORD.D method provides an estimate of the APs of each spectrum, which are obtained in an iterative procedure that optimizes the continuum normalisation of the observed spectrum as well as the cross-correlation function of the spectrum by a grid of synthetic spectra. Then a minimum distance method is applied on the epoch combined spectra of all available spectral domains of a given target in order to select the closest synthetic spectrum and APs. In addition, a first insight of the stellar content of the sample was performed by comparing each spectrum to observed templates selected from the HERMES library, providing as APs those of the nearest neighbour. Photometric temperatures were also estimated using different colour calibrations and combining the GEPC and 2MASS photometry. Therefore the Frémat et al.'s paper provides three different sets of APs for each target. The corresponding tables, including also the S/N of the spectra and the GEPC photometry, are available by sftp in the GBOG directory gbogcom at ssh.esac.esa.int, /gbog/cu6/SEP (password gbog4dpce). However these APs were not considered precise enough for CU8, that is why it was decided to redetermine the APs with the classical methods that use stellar atmospheres.

We reduced the data using the ESO pipeline (release 2.12.1). We also developed our own sophisticated methods to normalise, remove the telluric features for each spectrum and to determine the radial velocities. These methods were especially designed for these spectra. The normalisation was done using the template obtained from the cross-correlation function of RV correction from the method (1) described above. When several spectra were taken for the same star, we took the median of all of them to increase the SNR. This procedure was also done using the iSpec package, after correcting the spectra by barycentric velocity. The data are stored on the ESAC disk place created for GBOG working group: gbogcom at ssh.esac.esa.int, /gbog/cu3/SEP_SPECTRA/FLAMES/G.Merged/.

In this note, we concentrate on the analysis of only the high-resolution spectra, namely UVES and GIRAFFE HR21 (hereafter GIR-HR21). The UVES sample covers a wavelength range of 780-1000 nm and has a resolving power of 47,000 (unfortunately not all the RVS wavelength range is included in these spectra). The GIR-HR21 spectra include the RVS range, covering a wavelength range of 848-900 nm and having a resolving power of 16,200. Typical SNR of the spectra are 40 as measured with with iSpec, which takes the entire spectrum scans 10 by 10 flux measures. It calculates the ratio of the mean and the standard deviation of these given 10 flux measures. The final SNR corresponds to the mean ratio calculated for the whole spectrum [2]. The brightest stars have SNR above 200. We analysed the stacked GIR-HR21 data with the iSpec package for the stars that did not show signatures of radial velocity variability in various observations, i.e., they were classified as constant stars. A total of approximately 60 UVES and 400 GIR-HR21 are included in this analysis.

[2] see Sect. 3.1.4 of the iSpec manual found in http://www.blancocuaresma.com/s/iSpec/

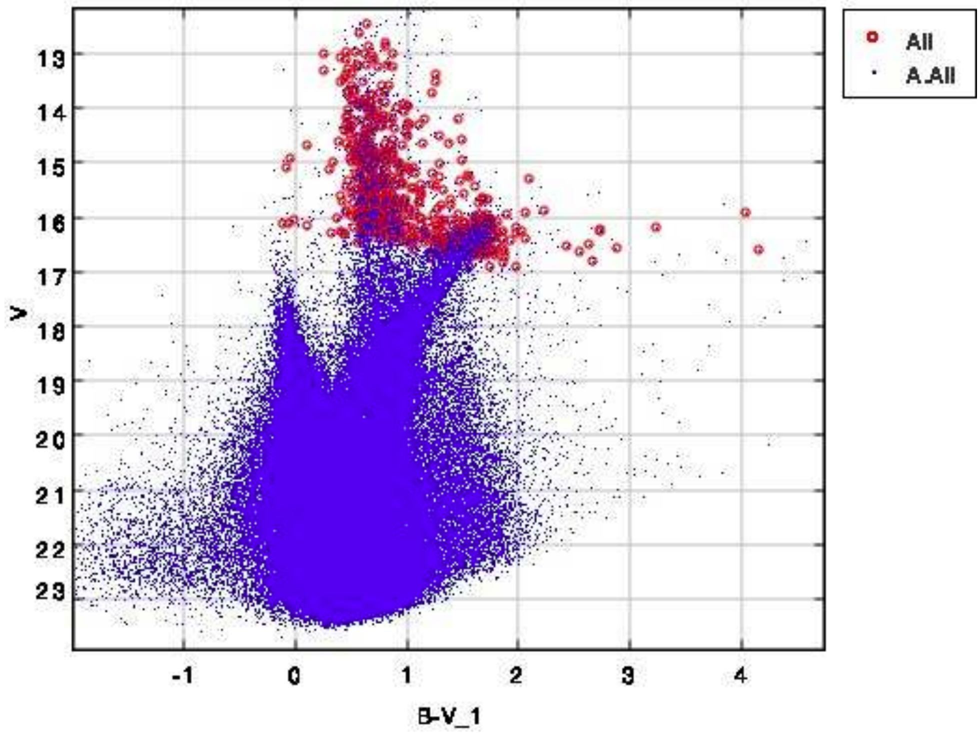

FIGURE 1: Colour magnitude of the EPC. Red circles correspond to the stars which have FLAMES spectra. Blue dots are all the stars belonging to the full EPC.

2.2 The calibration sample

In order to set and validate our methods, a calibration sample was needed. For that, we considered the Gaia FGK benchmark stars (Heiter et al., 2015; Jofré et al., 2014a,b), which are also used to scale other parameters from e.g. CU8 and the Gaia-ESO survey. We collected data of the benchmark stars for the UVES and the GIR-HR21 sample and built libraries, namely we corrected by radial velocity, convolved to the resolving power of our sample and normalised the spectra as described in Blanco-Cuaresma et al. (2014b). The UVES-like data comes from several sources: ESO public archive, UVES-POP library, NARVAL and ESPADONS public archives, and the Gaia-ESO Survey. The GIR-HR21-like data comes from the NARVAL and ESPADONS public archives, as well as the Gaia-ESO Survey.

3 Atmospheric parameters

3.1 Line list

Spectra at the UVES resolution in that wavelength range have not been studied much in the past, thus we spent significant effort in defining a line list for iron with good atomic data. This was done principally by N. Brouillet and U. Heiter in a similar fashion as the preparation of the line list for the Gaia-ESO survey. This is, new laboratory data was collected for all iron lines taken originally from the VALD database in the UVES range and from Pancino et al. (2010). For those lines with good data, syntheses were computed and the profiles were compared to an atlas of the Sun (a typical main-sequence star) and of Arcturus (a typical red-giant star). Since several targets are giants, a line list of molecules needed to be prepared for the analysis with syntheses. The data was kindly given by T. Masseron, which is the same one used for the Gaia-ESO Survey but adapted to the UVES CD#4 wavelength range. Because the molecular data are so large, including the complete list in the analysis was computationally too expensive. Therefore, several line lists were prepared by T. Nordlander to include the optimal amount of molecules depending on the temperature of the star.

For the GIR-HR21 spectra, we used the atomic line list already prepared for the Gaia-ESO Survey. Although the molecular data is also available, we have not prepared optimal lists for this setup yet.

3.2 Codes

The determination of parameters (effective temperature, surface gravity and global metallicity) has been done using four independent methods. Two methods are based on equivalent widths measurements and two methods are based on synthesis, which are briefly described below. The UVES spectra were analysed with all the methods, the GIR-HR21 spectra only with one method based on synthesis. Note that these methods to determine stellar parameters are fully spectroscopic, i.e., they are independent on extinction.

- PAD: Refers to the method employed in Padova by A. Vallenari, R. Sordo and T. Cantat-Gaudin. The method is based on equivalent widths as measured with DAOSPEC (Stetson & Pancino, 2008) and with DOOp (Cantat-Gaudin et al., 2014) in an automatic fashion. The parameters are then determined using FAMA (Magrini et al., 2013), which is code that allows automatic determination of parameters using the code MOOG of C. Sneden.
- BOL: Refers to the method employed in Bologna by E. Pancino. This method also uses equivalent width measurements from DAOSPEC + DOOp, but the parameters are determined using GALA (Mucciarelli et al., 2013), which is an automatic version of the WIDTH9 code developed by R. L. Kurucz.

- UPP: Refers to the method employed principally in Uppsala by T. Nordlander and U. Heiter. This methods determines parameters by computing synthetic spectra on the fly and fits profiles of certain lines. It is based on the SME code (Valenti & Piskunov, 1996).
- BOD: Refers to the method employed principally in Bordeaux by C. Soubiran and N. Brouillet. It also determines parameters by computing synthetic spectra on the fly and fitting profiles of certain lines. It is based on the iSpec code (Blanco-Cuaresma et al., 2014a) which synthesises spectra using the SPECTRUM code developed by R. Gray. This method is also referred as to iSpec in the analysis of the GIR-HR21 spectra as employed by P. Jofré in Cambridge.

While the synthesis codes are based on fitting the profile of lines at pre-defined masks, which include the wings of the Ca triplet and some iron and other strong lines, the equivalent widths approach concentrated only on excitation and ionisation equilibrium of iron lines. The very red part of the optical spectrum is so crowded by telluric features that very few clean iron lines with good atomic data remained, especially the ionised ones. For that reason, constraining the three parameters at once using equivalent widths techniques was impossible and surface gravity needed to be fixed to the values obtained from the synthesis methods.

3.3 Intial APs

As initial APs for the spectoscopic analysis, we used those determined for the RV work (see Sect. 2.1 and Frémat et al. A&A in preparation). For the UVES sample these were the photometric Teff estimated from the combination of the GEPC photometry in several filters and the 2MASS photometry. For the GIR-HR21 analysis, we used the APs estimated by XCOR.D (i.e. the APs of the synthetic spectrum optimising the cross-correlation).

4 Benchmark Stars

The benchmark stars serve to define the best masks for the synthesis codes and to test and validate the performance of our methods. In this section we show our results for UVES and GIR-HR21 separatedly.

4.1 UVES CD#4 spectra

In Fig. 2 we show the performance of the four methods on the library of benchmark stars in the UVES data. The four methods are plotted with different colours and symbols as explained in caption of the figure. The name of each star is indicated in the bottom of the figure. For completeness, we considered all the 34 benchmark stars, even if some of them were not part

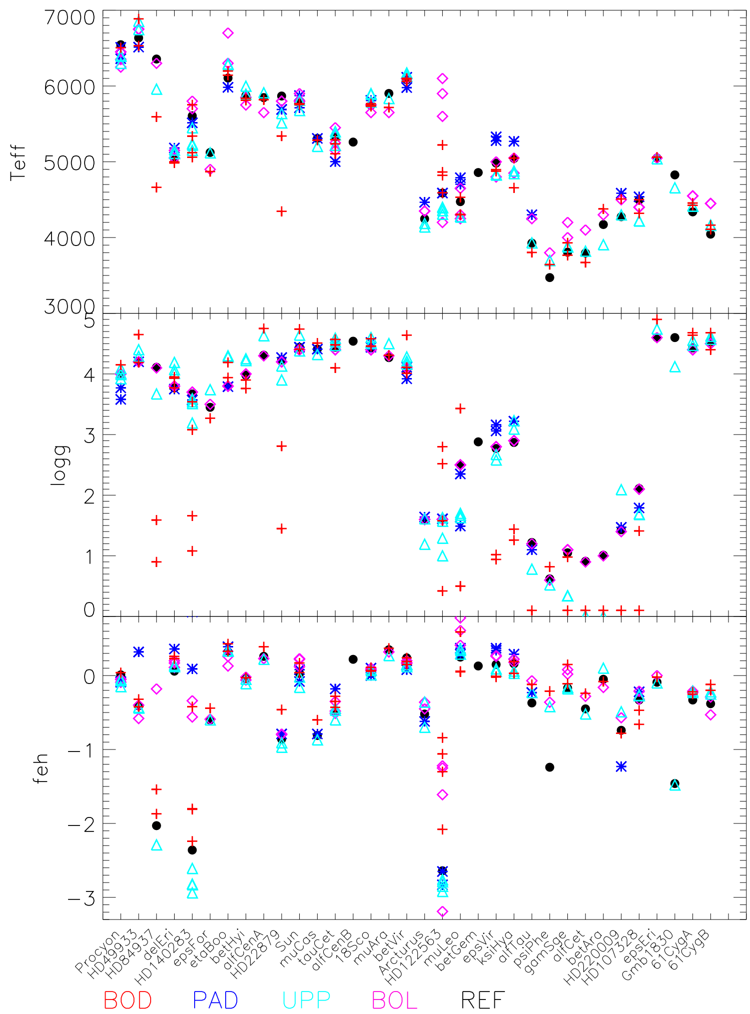

FIGURE 2: Atmospheric parameters of benchmark stars determined from the UVES CD#4 grating with four different methods. Red crosses represent the results from the BOD method, blue asterisks from the PAD method, cyan triangles from the UPP method, pink diamonds represent the results from the BOL method and black filled circles represent the reference values Jofré et al. (2014a).

of the libraries used in this particular analysis. In general, temperatures are well determined by all methods at all temperatures, which is an encouraging result. Surface gravities are more challenging, note the equivalent widths methods (PAD and BOL) are fixed to the reference value. The BOD method still has large difficulties to retrieve accurate surface gravities for some stars, especially the cool giants and metal-poor stars. The UPP method performs reasonably well in surface gravity for all benchmark stars, except the most metal-poor one HD122563. The four methods have a fairly good agreement in metallicities, with metal-poor stars being more problematic. One can see that the synthesis methods are able to retrieve metallicities for the metal-poor warm stars, while the equivalent width methods have trouble. We explain this issue with the lack of available strong iron lines with revisited atomic data.

We conclude that it is reasonable to deliver parameters as determined by the UPP method. This is because the UPP method retrieves the benchmark star effective temperatures, surface gravities and metallicities simultaneously and accurately. The method takes advantage of using synthetic spectra with molecules for the coolest giants and can determine parameters from other features beyond iron lines. This is important as this method allows us to use information in blended and crowded regions, which in many cases is the only features we have in these difficult UVES red spectra. However, the comparison and parallel development with several methods was crucial to assess and understand the accuracies and reliability of the UPP method. The external accuracies respect to the benchmark stars are of 150 K in temperature, 0.4 dex in surface gravity and 0.1 dex in metallicity.

4.2 GIR-HR21 spectra

A similar analysis was performed for two independent sets of benchmark stars in the HR21 range. One was done for the spectra taken by the Gaia-ESO survey (see Fig. 3). The advantage of this calibration sample is that the spectra are directly taken with the GIRAFFE HR21 setup and the normalisation was done in the same fashion as the SEP targets by Y. Frémat. Thus, this analysis gives us a fair idea of how well are we able to parametrise the SEP dataset. Similarly, the same iSpec pipeline was applied to a high-resolution library in the GIR-HR21 wavelength range considering data from ESO archives, NARVAL and ESPADONS as mentioned in Sect. 2.2. The advantage of this library is that it is of higher resolution ($R = 65,000$) and includes stars that are not observable in the Southern hemisphere by the Gaia-ESO Survey. The results are shown in Fig. 4.

The three parameters are well determined in this range for the bulk of the benchmark stars. Cases such as the metal-poor stars could not be analysed, the code did not converge to a meaningful value, probably to the lack of strong lines available in this narrow spectral range. Cool giants also have some problems in retrieving all parameters, with iSpec systematically retrieving higher metallicities and gravities than the reference values. The determination of parameters for cool giants is very challenging, especially in a small wavelength domain such as the GIR-HR21 range, but there is still space for improvement. On one side, a proper inclusion of molecules might improve our metallicities and thus our surface gravities for cool stars. Finally, we obtain for the Solar spectrum observed by the Gaia-ESO survey at different SNR a large range of gravity values, which is expected as this parameter is the most degenerate. The metallicity and effective temperatures show in overall a much constrained result. Further studies of our

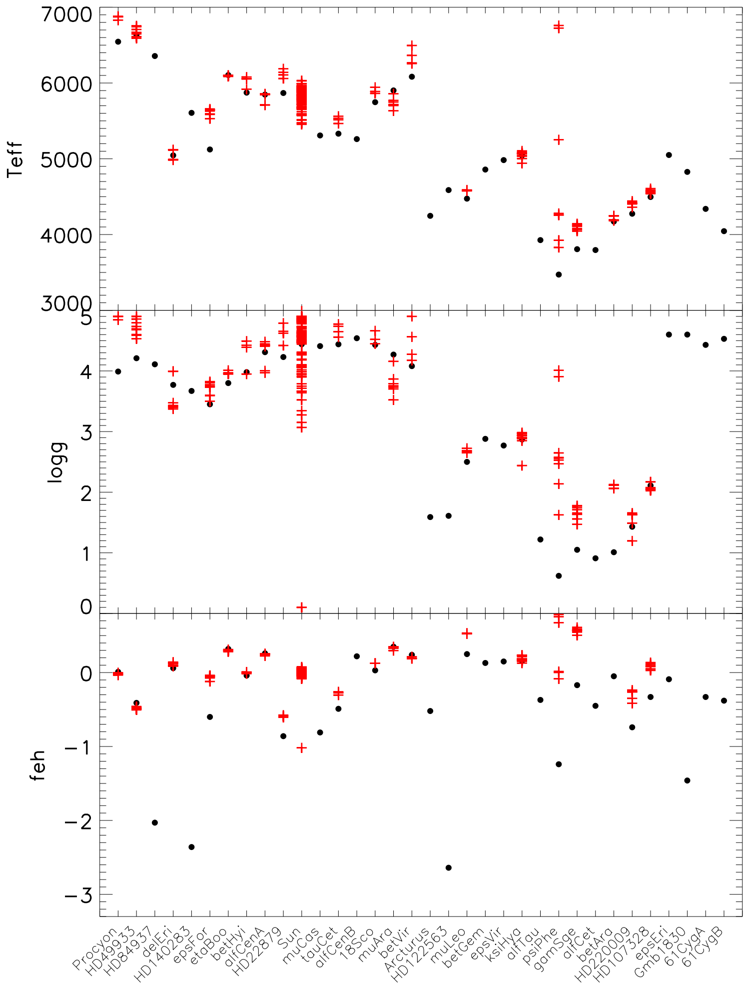

FIGURE 3: Atmospheric parameters of benchmark stars determined from the GIR-HR21 setup for the benchmark stars observed with GIR-HR21 setup by the Gaia-ESO Survey. Red crosses represent the results from the iSpec method and black filled circles represent the reference values Jofré et al. (2014a).

parameters as a function of SNR are needed to address the precision of this method. Compared to the benchmark stars, we retrieve effective temperatures within 200 K, surface gravities within 0.6 dex and metallicities within 0.3 dex.

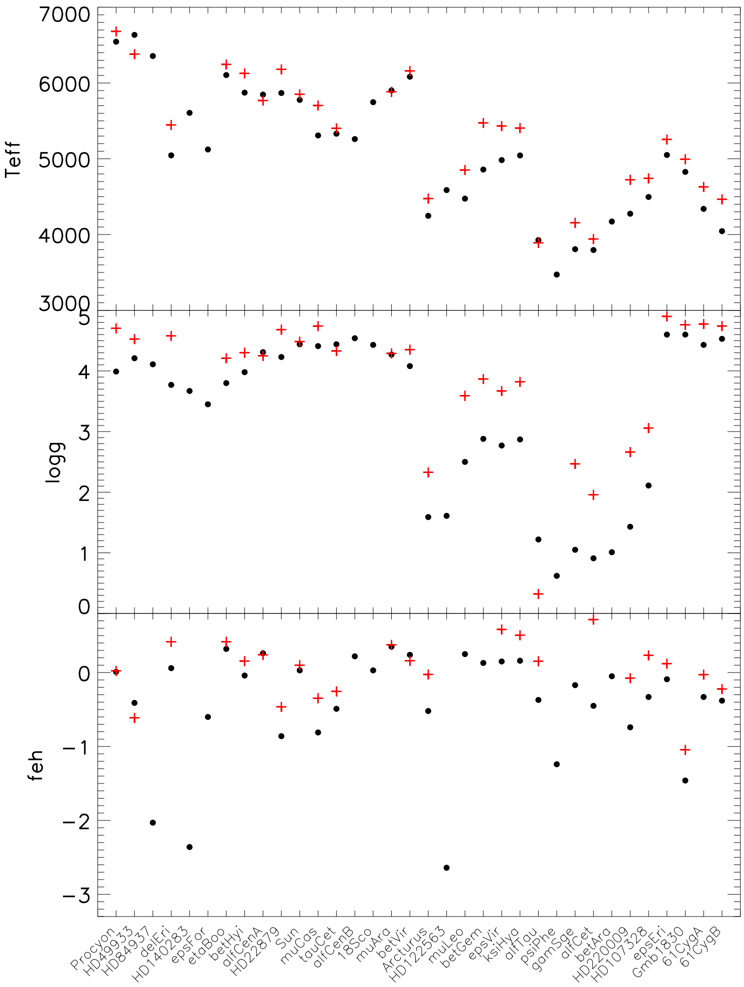

FIGURE 4: Atmospheric parameters of benchmark stars determined from the GIR-HR21 setup for the benchmark stars taken from high resolution archival data. Red crosses represent the results from the iSpec method and black filled circles represent the reference values Jofré et al. (2014a).

5 SEP field

At the time we publish this TN, not all the APs deduced from the different methods were avalaible. In the preliminary version of the SEP-AP catalogue described here, the GIR-HR21 APs are those obtained using the iSpec package (BOD), while the UVES APs are those obtained using the SME package (UPP). In Fig. 5 we display those results. The four panel figure shows the distribution of initial parameters (left, see Sect. 3.3) and those described in this TN (right) in the HR diagram (top) and in metallicity (bottom). The symbols, dots for GIR-HR21 and triangles for UVES, are plotted with two colours for each dataset: stars with RV$>$ 280 Km/s are interpreted to belong to the LMC; stars with RV$<$ 280 Km/s are interpreted to be part of the Milky Way field. The metallicity distribution of the GIR-HR21 for Milky Way and LMC stars are plotted with blue and red colour, respectively. With cyan we plot the distribution of the UVES sample. Only two stars observed with UVES have LMC RVs. Note some stars classified as LMC members have gravities that would have inconsistent distances to the LMC, suggesting that these stars might be high velocity halo stars misclassified as LMC stars. We plan to make a more detailed analysis of our targets to classified them into the different populations of the SEP field.

The first aspect to note from Fig. 5 is that the need of a detailed spectroscopic analysis for the determination of atmospheric parameters is clear. By using the input values of the cross-correlation function we are limited to have parameters within grid points only. Also, a detailed analysis allows us to take extra care for difficult stars, such as the LMC ones observed with UVES, which were misclassified as main sequence ones in the cross-correlation function. Furthermore, the HR diagram and metallicity distributions with spectral parameters gives us much more accurate overview of the stars in the SEP field.

From the HR diagram we can see the clear division of stars from the LMC and the Milky Way field. Since the targets were selected from their magnitudes only, it is expected that the LMC stars are ones that are intrinsically brighter, since they are more far away. Our parameters tell us that the LMC stars are the red giants, while the Milky Way field covers some red giants and main-sequence stars.

The metallicity distribution also shows consistent results, with the UVES and the GIR-MW sample peaking at a metallicity that is somehow higher than the GIR-LMC sample. This is expected because the LMC stars are more metal poor than the field stars of the MW thin disk.

The comparison of parameters for stars that have been observed in both setups is shown in Fig. 6. The UVES and GIR-HR21 APs are consistent. The parameters for GIR-HR21 and UVES spectra have been determined with different codes (BOD and UPP respectively), different line lists and on spectra that differ significantly in their resolution and spectral range (although the GIR-HR21 range is partly included in the UVES range). Therefore the good agreement suggests that our results are reliable. This comes from the efforts invested to calibrate the methods such that the parameters of the same stars, the benchmark stars, are well retrieved.

The agreement in the parameters is good, although there are some exceptions that need further investigations. For hot stars for example, we obtain differences of more than 500 K in temperature. Sub-giants also have gravities that might be off by 1.5 dex, and two stars are more difficult with differences larger than 1 dex. Removing the extreme cases (differences in parameters of

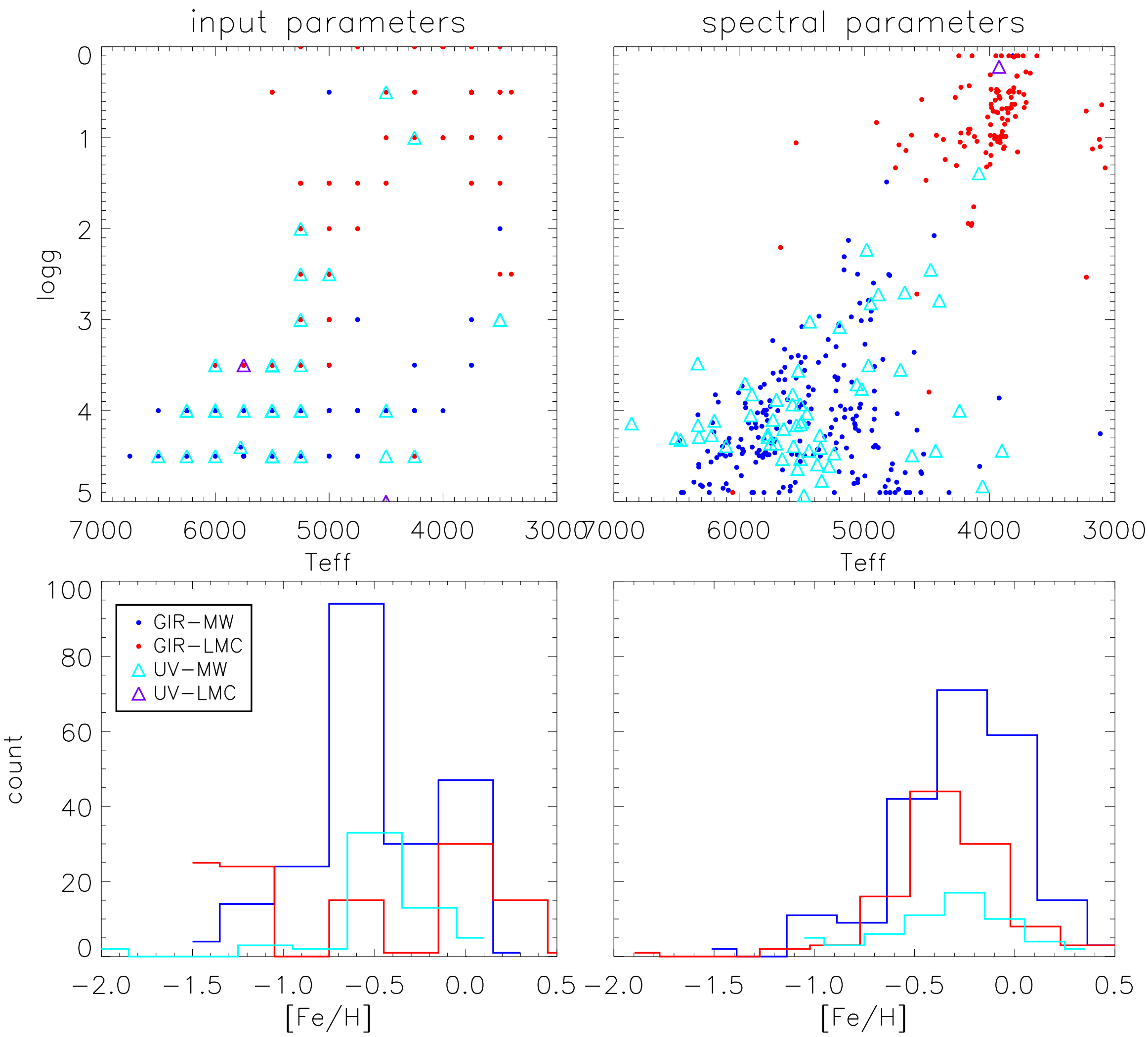

FIGURE 5: Top panels: logg - temperature diagrams of the targets observed in the SEP field. Dots correspond to the stars observed with the GIR-HR21 setup and triangles represent the stars observed with UVES. Based on their RV, the colour indicates the stars belonging to the Milky Way field and the LMC. The bottom panels represent the metallicity distribution of the different populations. The left hand panels consider the input parameters as obtained from the cross-correlation function for the RV determination, the right hand panels display the output parameters from spectroscopy.

more than what stated above) we obtain a good agreement within 300 K in temperature, 0.5 dex in gravity and 0.4 dex in metallicity, with no significant offset (UVES-GIRHR21) in gravity or metallicity, and 90 K in temperature.

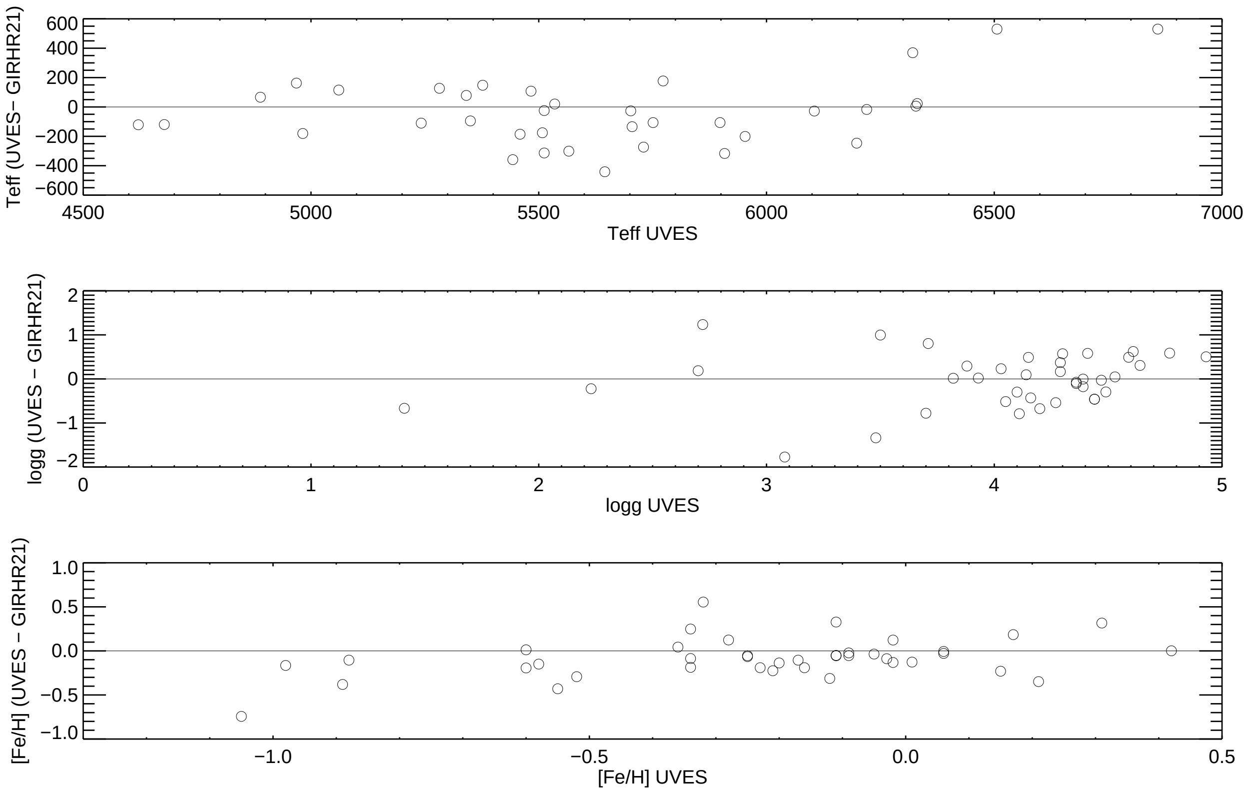

FIGURE 6: Difference of parameters for common stars in the SEP field observed with UVES and GIR-HR21 as a function of parameters

Finally we show how our effective temperatures derived from the spectra compare with those from photometric relations. This is shown in Fig. 7 for both datasets. The UVES sample shows a negligible offset (SPEC-PHOT) of –20 K with a considerable standard deviation of 310 K. The Giraffe sample has a slightly larger offset of 89 K with a similar standard deviation of 290 K. The results show to be consistent, although the photometric temperatures were considered as initial guess. The agreement between both temperatures could be improved considering the metallicity determined form the spectral analysis or considering extinction in the line-of-sight.

6 The SEP AP catalogue and future perspectives

The SEP AP catalogue will be included in the compilation of atmospheric parameters described in Soubiran et al. (CS-011), already used by CU6 and foreseen to be used by CU8 for the Apsis validation. It is an ascii file with the same format described in the Soubiran et al. (CS-011). Readme file and contains the necessary information for the cross-match with IGSL and other catalogues (identifier, coordinates, V and K magnitudes) and for its transformation into the gbin table auxAtmParam with the data model defined in Katz et al. (DK-015) as described in

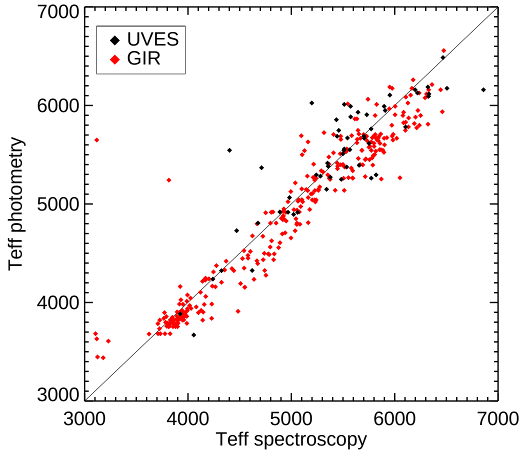

FIGURE 7: Difference of temperature determined from the spectra and from photometric relations for the UVES and GIR-HR21 sample.

Marchal et al. (OML-002). This SEP AP catalogue is stored on the ESAC disk space created for the GBOG WG: gbogcom at ssh.esac.esa.int, /gbog/cu8/SEP (password gbog4dpce).

The catalogue contains APs and their errors which combine external and internal uncertainties. The internal errors are the errors reported by iSpec and SME for Giraffe and UVES respectively. The external uncertainties are deduced from the agreement of our parameters and those of the benchmark stars. For the Giraffe dataset the external uncertainties correspond to 200 K, 0.6 and 0.3 dex for temperature, surface gravity and metallicity, respectively. For the UVES dataset the external uncertainties correspond to 150 K, 0.4 and 0.1 dex for effective temperature, surface gravity and metallicity. The total uncertainty was then obtained from the square root of the quadratic sum of internal and external uncertainty for each parameter. We plan to investigate in detail the sources of uncertainties in our parameters in the future, to achieve better precision in our measurements. The catalogue includes only the targets that have a 2MASS identification, corresponding to about 95% of the total sample. The Readme of the catalogue is given in the last page of Soubiran et al. (CS-011).

In the coming year we plan to keep working with this sample, in particular, we will determine the parameters of the stars that are not RV constant. We will also keep improving our parameters, especially the gravities and metallicities, for giant stars, by including the full treatment of molecules in iSpec and by adding larger calibration samples of giants. A very good candidate is the GES-CoRoT sample, which provides accurate gravities from asteroseismology combined with accurate effective temperatures and metallicities from spectroscopy. A sample of about 100 giants have been observed with HR21 in Gaia-ESO. Finally, we will investigate the extreme cases where large disagreements in the parameters for common stars between GIR-HR21 and UVES are seen. This will help us assessing better the internal systematic between our methods.

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Acronym List

The following table has been generated from the on-line Gaia acronym list:

Acronym	**Description**
EP	Ecliptic Pole
ESO	European Southern Observatory
GEPC	Gaia Ecliptic Pole Catalogue
GBOG	Ground-Based Observations for Gaia (DPAC)
LMC	Large Magellanic Cloud
MW	Milky Way
RV	Radial Velocity
RVS	Radial Velocity Spectrometer
SEP	South Ecliptic Pole
TN	Technical Note
VLT	Very Large Telescope