Building a catalogue of AP reference stars for Apsis

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Abstract

This TN describes the selection of FGKM stars which could be used for the external calibration and/or validation of the stellar parametrizers in Apsis. It explains how the APs of these stars will be homogeneously determined from high-resolution spectra.

Document History

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Contents

1 Introduction

The stellar parametrizers in Apsis, GSP-Phot, GSP-Spec and ESP, are trained on simulated spectra generated from synthetic ones which do not reproduce perfectly real Gaia spectra. This is known as the spectrum mismatch problem. One approach to minimize this problem and derive realistic error bars is to apply a calibation based on stars with APs known in advance with a high accuracy (but still model-based), and observed by Gaia in good conditions. This is not yet completely fixed whether the Apsis stellar parametrizers will use such an empirical calibration, or won't apply any calibration at all. Tests will be done in due time to evaluate the pros and cons of using a calibration or not. Such tests will need good reference stars anyway. DU811 proposes to apply calibrations with two levels of reference stars (Heiter et al. UH-001). At the first level, we define a set of benchmark stars made up of a small number of carefully selected, well-studied bright stars (around 40 FGKM and 20 OBA stars). For the chosen FGKM benchmark stars, Hipparcos parallaxes, angular diameters and bolometric fluxes are known, their masses were determined in a homogeneous way, so their effective temperatures and surface gravities were derived independently of spectroscopy (Heiter et al. in preparation). A library of high-resolution spectra was built by Blanco-Cuaresma et al. (2014b), and their metallicity was determined by Jofré et al. (2014). At the second level, we define a much larger set of several hundred reference stars covering the AP space more densely than the benchmark stars. Following what we did with the benchmark stars, we will (1) build a homogeneous library of high resolution spectra for the AP reference stars, (2) gather their photometry and Hipparcos parallaxes when available to constrain as well as possible their effective temperatures and surface gravities independently of spectroscopy, (3) determine their AP based on the library of high resolution spectra with a method already calibrated on the benchmark stars.

The ground-based auxiliary data available for OBA stars for the testing and training of ESP-HS are described in AJL-002.

Once an appropriate sample of reference stars is defined, the calibrations can be applied in two ways. In the data-side calibration, the training data are modified, while in the AP-side calibration, the resulting AP estimates are corrected. If no calibration is finally applied to the Apsis stellar parametrizers, the sample of reference stars will be needed anyway for the validation and for helping us to understand the Apsis results and models.

One important aspect of the DU811 calibration plan is to provide the basis of a common metallicity scale for all the spectroscopic surveys, based on the benchmark stars. The Gaia ESO survey has adopted this calibration plan and is currently observing benchmark stars. The Australian HERMES survey is also willing to observe the benchmark stars for the same purpose. The different spectroscopic surveys are complementary and it is important that they can be exploited jointly for galactic and stellar studies. This will be possible only if the parameters are on a common and homogeneous scale. The benchmark stars being not numerous and faint enough to serve as calibrators for all the spectroscopic surveys, the AP reference stars are proposed in complement.

In this TN we describe the high resolution spectra which are available for the FGKM AP reference stars, and the method used to build a library and determine their atmospheric parameters in a homogeneous way.

2 Criteria for selecting AP reference stars

Some requirements for the standard stars for GSP-Phot are expressed in RAN-011. The (unbiased) external errors on their AP should verify :

- T_{eff} accuracy much lower than 100K,
- A_0 accuracy much lower than 0.07mag,
- $\log g$ accuracy much lower than 0.35dex,
- [Fe/H] accuracy much lower than 0.25dex.

To have a high enough signal-to-noise ratio of their BP/RP spectra, the reference stars should have $G < 15$.

The reference stars should provide a good coverage over AP space. In terms of number of standard stars, 100 is estimated to be a minimum, $\sim$4000 would be ideal.

It is assumed that the calibration needs for GSP-Spec are similar, with a brighter magnitude range for the reference stars.

Our strategy to build the catalogue of FGKM AP reference stars for CU8 is first to gather high quality spectra from different sources, and to determine their AP. In a second time, the coverage of the AP space and magnitude range will be optimized, if needed.

3 Gathering high-resolution spectra of AP reference stars

To determine accurate AP of the reference stars, we need spectra of good quality, with resolution $> 40\,000$, and signal-to-noise ratio (SNR) > 40. Several sources are available to collect such spectra.

3.1 GBOG programmes

We have obtained observing time on the spectrograph NARVAL at Pic du Midi in the frame of the GBOG Working Group, to collect auxiliary data for CU8 and CU6. NARVAL has a resolving power of $\sim 80\,000$ in its spectrocopic mode, and $\sim$65 000 in its polarimetric mode. Between 2007 and 2012, we have obtained more than 1000 spectra, the majority for the follow-up of the RV standard stars for CU6 which does not require a high SNR. Once the asteroids and low SNR spectra removed, we have 904 useful spectra of 587 stars. These spectra have been used to build a library of empirical spectra for the RVS described in LCH-002 and mentioned in Sect. 3.4.

3.2 The ELODIE and SOPHIE archives

ELODIE and SOPHIE are two velocimeters successively mounted on the T193 telescope at OHP, with resolving power of $R = \lambda/\Delta\lambda \simeq 42\,000$ and $75\,000$ respectively. SOPHIE also has a high efficiency mode to observe fainter stars, and in this mode the resolving power is $R = 40\,000$.

The ELODIE archive (Moultaka et al., 2004) includes 35 535 spectra. The relevant information (SNR, date of observation, cross-correlation, etc) can easily be retrived form as a single file by a command of this type : `http://atlas.obs-hp.fr/elodie/E.cgi?n=501&a=t&d=objname,datenuit,imanum,sn,jdb,vfit,sigfit,ampfit,vfit2,sigfit2,ampfit2,masque,imatyp`.

From this list, only spectra with SNR > 40 were considered. We keep only stars which can be identified with a HIP, TYC or 2MASS number. This is to ensure that the cross-match with the IGSL can be done. The exposures with a thorium-argon calibration lamp taken simultaneously on the second fiber were rejected because it is suspected that saturated argon lines can pollute the stellar spectrum and affect the AP determination. After this cleaning, 3856 useful spectra remain, for 1940 different stars. 97% of them are part of the AP compilation described in CS-011, mostly for Teff, but 1189 have the 3 atmospheric parameters available from the literature (see Fig. 1).

As of early March 2014, there were more than 71 200 spectra for 5 230 distinct targets in the SOPHIE archive. Almost 37 500 spectra are fully public and more than 28 000 spectra are available with the exact time of observation masked (for a 5-year period), while nearly 4 900 spectra are under the standard 1-year embargo. Similar cleaning as for the ELODIE archive gives 13884 useful spectra of 2856 stars in the HR mode, and 2240 useful spectra of 446 stars in the HE mode. AP are available for 1861 stars from CS-011 as shown in Fig. 2.

3.3 The ESO archive

The selection of FEROS and HARPS spectra are done on the basis of the AMBRE catalogues. The spectra of interest will be dowloaded from the ESO Archive facility. The AMBRE-FEROS catalogue of AP includes 6508 spectra of 3087 stars (Worley et al., 2012). The AMBRE-HARPS catalogue of AP is based on the analysis of 90 174 spectra of 10 706 stars De Pascale et al. (2014). AMBRE-UVES is in preparation (de Laverny, private communication).

Although the AMBRE catalogues contain several thousands of stars with APs determined homogeneously, they are not optimal to serve as reference for CU8 for the following reasons :

- AMBRE APs are based on the MATISSE code (Recio-Blanco et al., 2006) also used in GSP-Spec. The external APs for the CU8 calibration should be independent of those determined by Apsis.

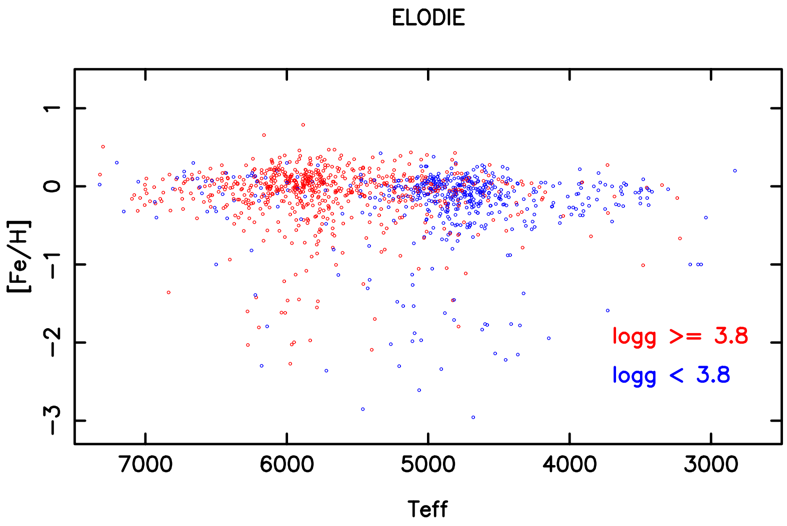

FIGURE 1: Distribution of AP for 1189 stars in the ELODIE archive which have AP available from the literature and compiled in CS-011

- AMBRE does not provide a homogeneous spectral library as an output. Following the work done with the benchmark stars, we will build a homogeneous library of high resolution spectra and make it public. It will be available for other groups or spectroscopic surveys to test automated methods of stellar parametrization.
- AMBRE APs are not calibrated on benchmark stars. Our method to determine the APs of the reference stars (see next section) has already been calibrated with the benchmark stars, and uses a homogeneous library
- AMBRE is a southern catalogue. It is better to have AP reference stars in both hemispheres. Although not a CU8 requirement, this is useful that Gaia AP reference stars are observable by other spectroscopic surveys.
- AMBRE determines an overall metallicity and alpha enrichment while we intend to determine accurate abundances of iron and several other elements.

After removing the lowest SNR spectra from AMBRE-FEROS, 2569 stars remain, which are shown in the Teff-[Fe/H] plane in Fig. 3. Interestingly, there are structures in the parameters for

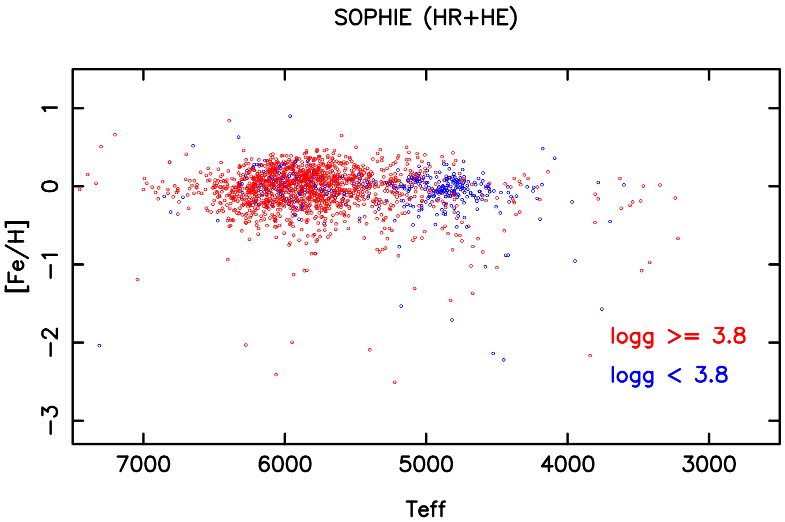

FIGURE 2: Distribution of AP for 1861 stars in the SOPHIE archive which have AP available from the literature and compiled in CS-011

giants (a clustering at several Teff values). These structures are also seen in the original paper of Worley et al. (2012) in their Fig. 15, and can be due to a bias of the method. For AMBRE-HARPS, the same cleaning results in 1538 stars shown in Fig.4. Compared to the other sets, the fraction of giants in AMBRE-HARPS is much lower.

3.4 NARVAL and ESPaDOnS spectra for the RVS

The library of empirical spectra for the RVS (LCH-002) includes 1238 spectra from the NARVAL and ESPaDOnS spectropolarimeters, all with SNR >70, and R $>$ 65 000. Most of the NARVAL spectra are from our GBOG observations mentionned in Sect. 3.1. The other ones come from POLARBASE (Petit et al., 2014).

In addition, we have 166 NARVAL spectra with $40 \leq$ SNR < 70, corresponding to 125 stars, mostly in open clusters and at North Ecliptic Pole.

Fig. 5 shows the 500 FGKM stars from the library which have AP available in the CS-011

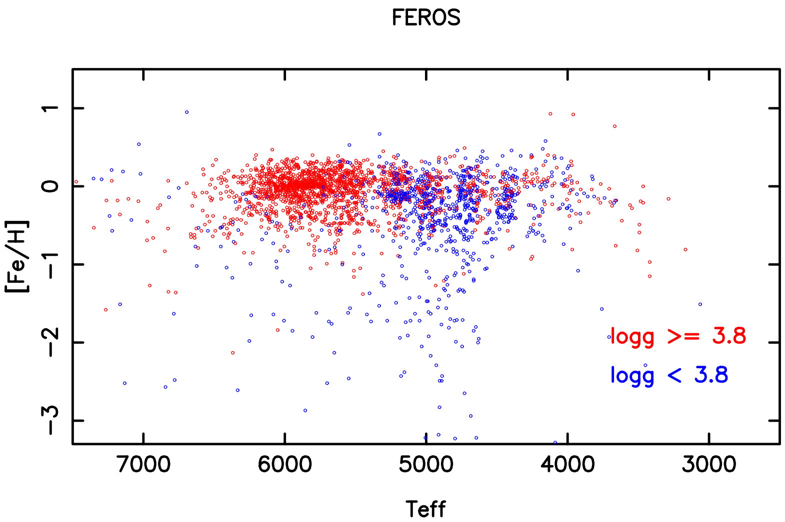

FIGURE 3: Distribution of APs for 2569 stars in AMBRE-FEROS

compilation.

3.5 Cluster stars

Open and globular clusters are interesting objects for the calibration of algorithms because of the common chemical composition of their member stars. Open cluster stars have been observed in the GBOG framework for this purpose. The spectra, together with archived data for a total of 177 stars in 31 open clusters, have already been homogeneously analysed by Blanco-Cuaresma et al. (2015). More stars in open and globular clusters are currently observed with UVES as part of the Gaia ESO survey. We hope to be allowed to include these high-resolution spectra in our dataset once they will be public.

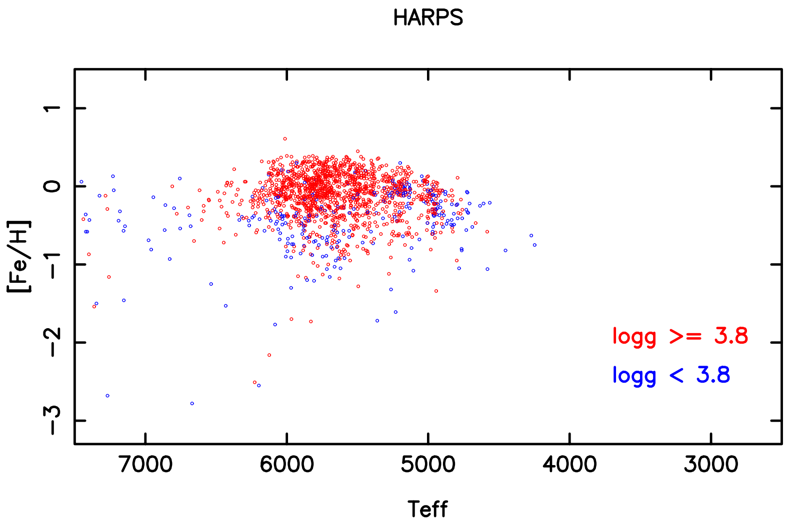

FIGURE 4: Distribution of APs for 1538 stars in AMBRE-HARPS

4 Combining high resolution spectra into a homogeneous library

Table 2 summarizes the number of spectra with SNR > 40 available from the different archives and their characteristics. In total they represent 9441 different stars. Fig. 7 shows their distribution in V magnitude and B-V colour. It is worth to note that not only FGKM stars are available in this sample. There are a number of blue stars, with B-V < 0.35 which correspond to OBA stars. We won't analyse these spectra, but they might be useful for the calibrations of ESP-HS (Lobel A. et al., AJL-002).

Fig. 6 displays the HR diagram of the 6 599 stars which have (Teff, logg, [Fe/H]) known from the CS-011 compilation, in 4 different metallicity ranges typical of the halo, thick disk, thin disk and metal rich populations. Stars with thin disk metallicities are much more represented in the sample compared to the other types of stars. This is a bias due to the observational programmes on velocimeters. The number of relevant reference stars can be reduced by selecting only a fraction of these stars so that the coverage of the parameter space will be more homogeneous.

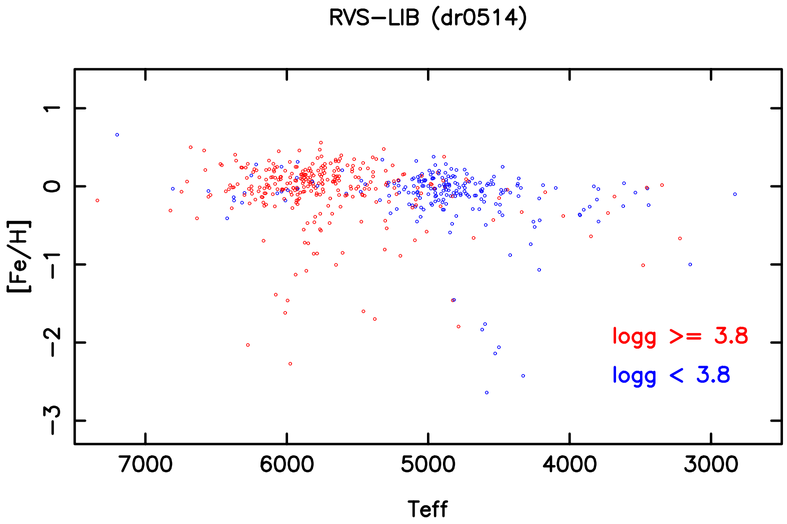

FIGURE 5: Distribution of AP for 500 stars in the RVS library which have AP available in the CS-011 compilation

Metal-poor stars and cool dwarfs are less represented because they are fainter and not easy to observe at high resolution and high SNR with telescopes of the 2-4 meter class. However many cool dwarfs are available in the archives of velocimeters because of exoplanet searches focused on these stars. They do not appear on the plots because their APs, very difficult to determine due to molecular bands, are not available in the literature. We will have the difficult task to properly determine their APs. More metal-poor stars may need to be included in the sample of AP reference stars. They will be searched in the UVES archive at ESO, and later in the UVES part of the Gaia ESO survey.

Following the work done with the benchmark stars (Blanco-Cuaresma et al., 2014b), a homogeneous library will be built and made public. All the spectra will be degraded to a common resolution of 40 000 and restricted to the spectral range 480-680 nm (the bluest range is not considered because of lower SNR). Multiple exposures of the same star will be co-added to improve the SNR. The iterative continuum normalization explained in Blanco-Cuaresma et al. (2014b), and refined in Blanco-Cuaresma et al. (2015) will be applied.

The resulting library will be useful for other groups or spectroscopic surveys to test automated

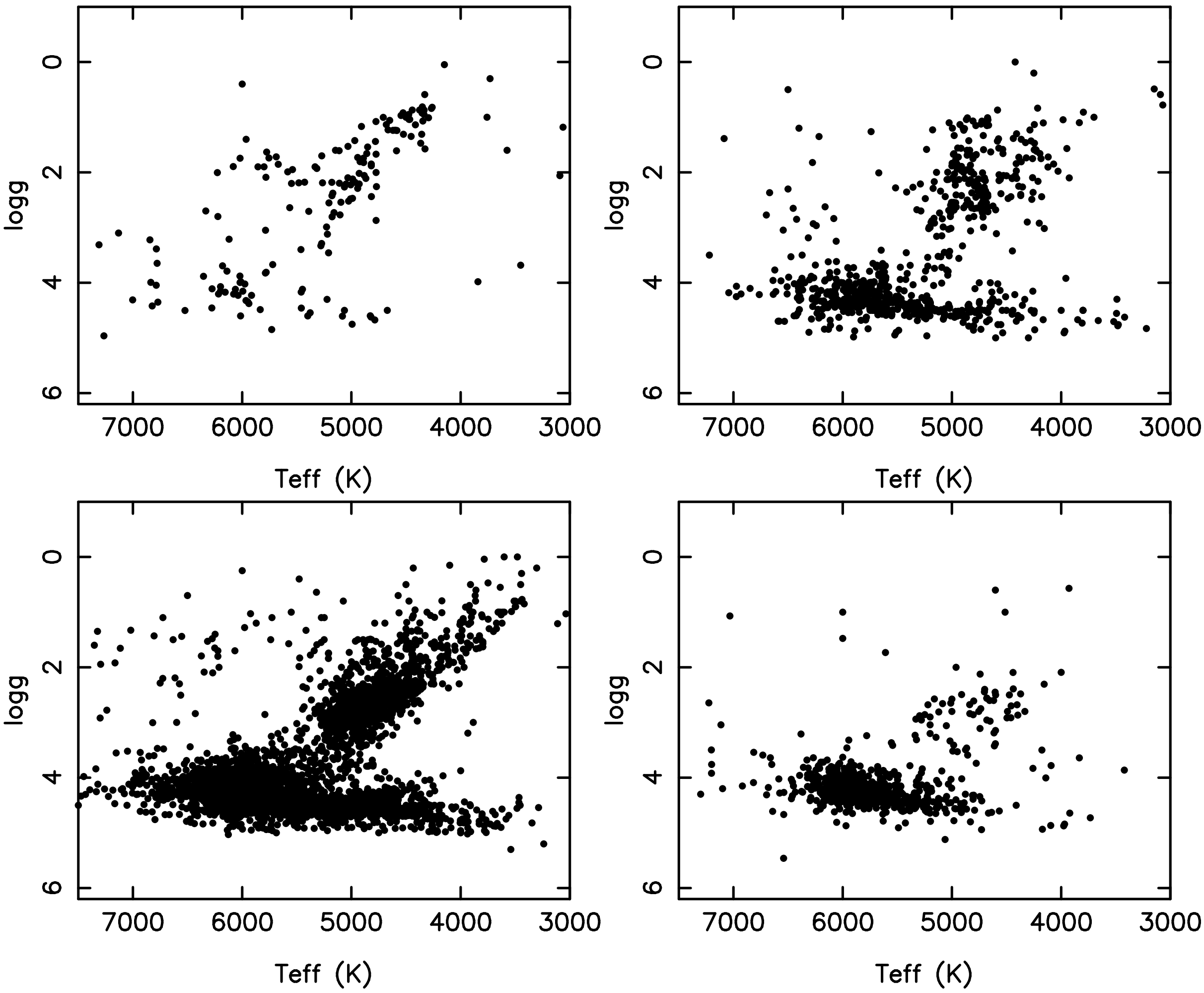

FIGURE 6: Teff vs logg in four different ranges of metallicity : [Fe/H]< -1.2 (upper left), -1.2 ≤ [Fe/H]< -0.4 (upper right), -0.4 ≤ [Fe/H]< +0.2 (lower left), [Fe/H] ≥ +0.2 (lower right)

methods of stellar parametrization and calibrate their APs. The library can be degraded to a lower resolution to fit various calibration needs.

5 AP determination for the reference stars

First, we intend to constrain effective temperatures and surface gravities as much as possible independently of spectroscopy. For Teff, colour calibrations can be used. The relations Teff vs V-K and other colours can be re-calibrated from the benchmark stars. Alternatively, we could use the relations of González Hernández & Bonifacio (2009) which are well adapted for FGK dwarfs and giants. The photometry in different bassbands is also important to constrain the extinction. Some 80% of the ∼9000 stars identified in the previous section are in the Hipparcos

TABLE 2: Summary of available spectra

Spectrograph	Resolution	$\lambda\lambda$ (nm)	N spectra	N stars
ELODIE	42 000	385-680	3856	1940
SOPHIE-HR	75 000	387-694	13884	2856
SOPHIE-HE	40 000	387-694	2240	446
NARVAL	80 000	370-1 050	904	587
ESPaDOnS	65 000	370-1 050	313	313
FEROS	48 000	350-920	5340	2569
HARPS	115 000	378-690	83067	1538

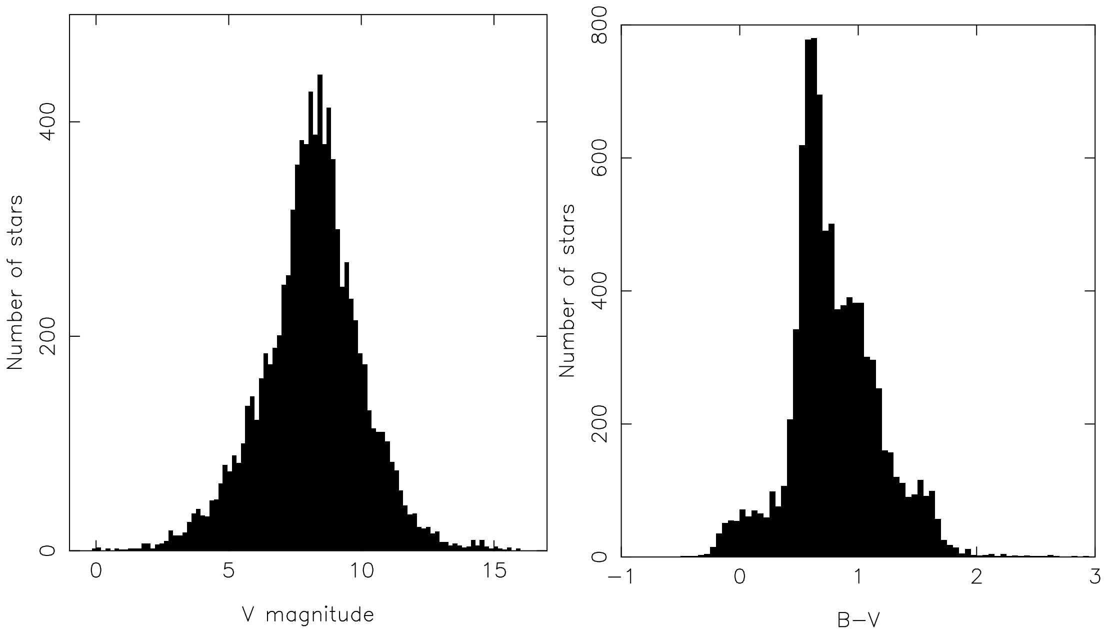

FIGURE 7: Histograms of the V magnitudes and B-V colours for all the ~9000 stars listed in Table 2

catalogue. Thus, with parallaxes, gravities can be infered from stellar evolutionary tracks using effective temperatures, luminosities and metallicities. It is worth to note that Gaia parallaxes will be available for all the AP reference stars in about 2 years, so that their gravities can be infered similarly, provided that the extinction is well constrained.

The iSpec code (Blanco-Cuaresma et al., 2014a) will be used together with the Gaia ESO line list (Heiter et al., in preparation) for the determination of the atmospheric parameters by synthetic spectral fitting, in an automatic way. The line-list covers our wavelength range of interest and it also provides a selection of middle and high-quality lines (based on the reliability of the oscillator strength and the blend level) for iron and other elements (e.g., Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Sr, Y, Zr, Ba, Nd, and Sm). The MARCS model atmospheres (Gustafsson et al., 2008) are adopted with the solar abundances from Grevesse et al. (2007). It is worth to note that the MARCS models are also used to generate some of the synthetic spectra used to train the Apsis algorithms. If known with a sufficient accuracy from the direct method, Teff and/or logg can be fixed. Otherwise, Teff and logg are let free and are determined spectroscopically. A fully automatic pipeline has been developed and calibrated on the Gaia FGK benchmark stars. It has already been used to analyse open cluster stars (Blanco-Cuaresma et al., 2015) and we will follow the same iterative process which optimizes the normalization of the spectra. This process also determines the individual abundances of more than 10 elements (depending on the type of stars).

The analysis of a single spectrum can take a few minutes to ∼2 hours of CPU time. The total time of analysis will be reduced by parallelizing the work using several multiprocessor computers available in Bordeaux.

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Acronym List

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

Acronym	Description
2MASS	Two-Micron All Sky Survey
AP	Astrophysical Parameter
CPU	Central Processing Unit
ESO	European Southern Observatory
ESP	Extended Stellar Parametriser
ESP-HS	Extended Stellar Parametriser Hot Stars
GBOG	Ground-Based Observations for Gaia (DPAC)
GSP-Phot	Generalised Stellar Parametriser PHOTometry
GSP-Spec	Generalised Stellar Parametriser SPECtroscopy
HE	High-Efficiency
HR	High-Resolution
IGSL	Initial Gaia Source List
MATISSE	MATrix Inversion for Spectral SynthEsis (software)
OHP	Observatoire de Haute Provence (France)
RV	Radial Velocity
RVS	Radial Velocity Spectrometer
SNR	Signal-to-Noise Ratio (also denoted SN and S/N)
TN	Technical Note
UVES	UV-Visual Echelle Spectrograph (VLT)