# The AMBRE Project: Stellar Parameterisation of ESO Archived Spectra

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**AMBRE is a Galactic archaeology project set up by ESO and the Observatoire de la Côte d'Azur in order to determine the stellar atmospheric parameters for the archived spectra from the ESO spectrographs FEROS, HARPS, UVES and GIRAFFE. A total of about 230 000 spectra have now been homogeneously analysed and, for most (i.e., the slow-rotating FGKM-type stars), parameterised by their effective temperatures, surface gravities, global metallicities, α-element to iron abundance ratios and radial velocities. The determination of the stellar parameters is carried out using a pipeline that has been specifically developed for AMBRE. This pipeline is based on the MATISSE algorithm initially developed for the analysis of the Gaia Radial Velocity Spectrometer data.**

## AMBRE: A Galactic archaeology project

Our understanding of the formation and evolution history of the Milky Way has undergone a revolution within just the last decade, owing to the advent of large spectroscopic surveys. These target anything from several thousand up to a few tens of millions of Galactic stars. Past and future Galactic surveys will allow us to trace, with unprecedented detail, the chemical and kinematic history of the Galaxy through an extensive characterisation of its stellar populations, including the oldest low-mass stars formed at the earliest epochs (the fossils of Galactic archaeology). European astronomy plays an important role in such Galactic archaeology surveys and its place will be strengthened in the coming years due to the ESA/Gaia mission (with its Radial Velocity Spectrometer [RVS]) and the complementary ground-based project, the Gaia–ESO Survey (GES; Gilmore et al., 2012). Recio-Blanco (2012) provides more details about these Galactic surveys, including past and future ones.

In this context, the AMBRE project (AMBRE stands for Archéologie avec Matisse Basée sur les aRchives de l'ESO) was established by ESO and the Observatoire de la Côte d'Azur in 2009 to automatically and homogeneously parameterise stellar spectra archived at ESO. AMBRE analyses the stellar spectra collected with the four ESO high-resolution spectrographs FEROS, HARPS, UVES and GIRAFFE. In total, this dataset consists of more than 326 000 spectra that were collected between 2000 and 2011 (see Table 1).

The main goals of AMBRE are:
- To provide ESO with a database of stellar parameters (stellar radial velocity, effective temperature, surface gravity, mean metallicity and the [α/Fe] chemical index, together with their associated errors) for the archived spectra from the ESO high-resolution instruments. The goal is to make these parameters available to the community and to encourage future use of the ESO archive.
- To rigorously test automated parameterisation algorithms on large spectral datasets covering various ranges in wavelength and resolution, including those adopted by present and future Galactic spectroscopic surveys. The AMBRE project is, for example, connected to the work package that parameterises the Gaia/RVS spectra (DPAC/CU8/GSP-Spec). The AMBRE atmospheric parameters are available for use as standard or calibration data for GES and Gaia.
- To create chemical and kinematical maps of the different Galactic stellar populations in order to carry out Galactic archaeological analysis together with providing new constraints to stellar evolution models based on homogeneous and statistically significant data.

The analysis of the data from the first three spectrographs (FEROS, HARPS and UVES) has now been completed and the data products are under delivery to the ESO Science Archive through Phase 3. They are now publically available[1]. In the following sections we briefly describe the status of the AMBRE project, the pipeline analysis on which it is based and present some data produced by this project.

## The AMBRE analysis pipeline

The spectra of FGKM-type stars archived by ESO are automatically and homogeneously analysed with a pipeline that has been specifically developed within the AMBRE project.

First, we received the reduced spectra for the four spectrographs from ESO. These spectra resulted from a re-analysis of the observed data by the ESO Data Management and Operations department using an improved reduction pipeline. This has ensured a very high homogeneity in the input data for the AMBRE project. Most of these reduced spectra can be retrieved from the ESO archives.

The AMBRE pipeline is based on the stellar parameterisation algorithm, MATISSE (Recio-Blanco et al., 2006), which was initially developed by the Observatoire de la Côte d'Azur for the analysis of Gaia/RVS spectra. It is a projection-like method that relies on a grid of synthetic spectra upon which the algorithm is trained. MATISSE has been applied to several Galactic archaeology projects, one of them being AMBRE. Other examples of the application of MATISSE are the stellar parameterisation of GIRAFFE spectra for the study of the CoRoT fields (Gazzano et al., 2010) and of the thick disc outside the Solar Neighbourhood (Kordopatis et al., 2011), as well as the last data release (DR4) of the RAVE Galactic Survey (Kordopatis et al., 2013). MATISSE is also one of the algorithms being used to characterise FGK-type stars in GES (UVES and GIRAFFE spectra).

| Spectrograph | Number of spectra | Observations | Publication |
|---|---|---|---|
| FEROS | 21 551 | 2005–2009 | Worley et al. (2012) |
| HARPS | 126 688 | 2003–2010 | De Pascale et al. (2013) |
| UVES | 78 593 | 2000–2010 | Worley et al. (2013) |
| GIRAFFE | > 100 000 | 2004–2011 | Under analysis |

**Table 1.** The spectra samples for the AMBRE project.

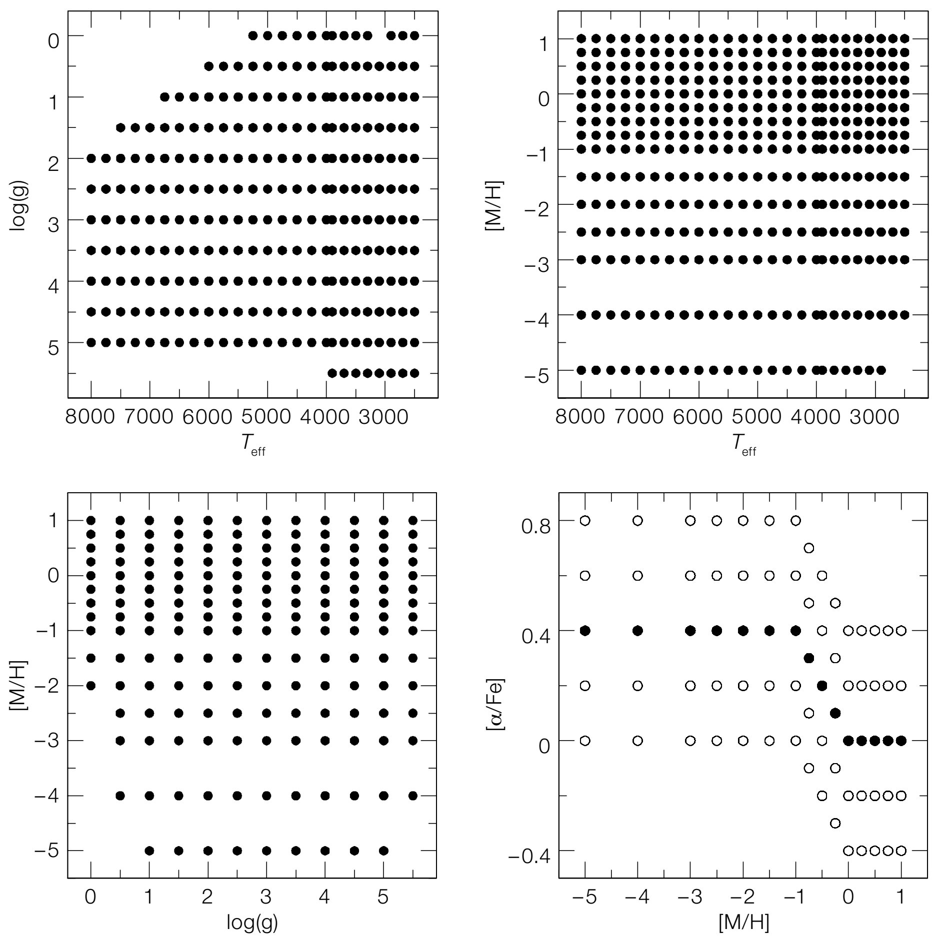


Figure 1. Distribution in the atmospheric parameter and [α/Fe] space of the FGKM-type synthetic spectra grid upon which the AMBRE pipeline is based (see de Laverny et al., 2012 for more details).

As a first step, a specific grid of about 17 000 synthetic spectra was computed for the AMBRE project (de Laverny et al., 2012). So that any of the spectral ranges and resolutions of the ESO spectrographs can be studied, this grid covers the whole optical domain for cool to very cool stars of any luminosity (from dwarfs to supergiants) with metallicities varying from $10^{-5}$ to 10 times the Solar metallicity. It also considers large variations in the chemical composition of α-elements with respect to iron. The parameter space covered by this grid is illustrated in Figure 1.

The analysis pipeline (see Figure 2) integrates spectral cleaning, signal-to-noise ratio (SNR) estimates, radial velocity determinations (including indicators sensitive to the projected rotational velocity) by cross-correlation with masks specifically built within the AMBRE project, radial velocity correction and iterative spectral normalisation procedures, and, finally, the automatic parameterisation of the spectra *per se*. Specific wavelength domains were also selected for each spectrograph in order to optimise the analysis computational time and accuracy (for instance, spectral ranges polluted by telluric features and the start and end of spectral orders with lower SNR are disregarded). This pipeline was first developed for the analysis of FEROS spectra (Worley et al., 2012) and it has been the testbed for producing the tools that are used in the analysis of UVES (Worley et al., 2013), HARPS (De Pascale et al., 2013) and GIRAFFE archived spectra.

The main products of this pipeline are the stellar radial velocity, the stellar atmospheric parameters (effective temperature, surface gravity and mean metallicity), and the enrichment in α-elements versus iron abundances ([α/Fe] chemical index)

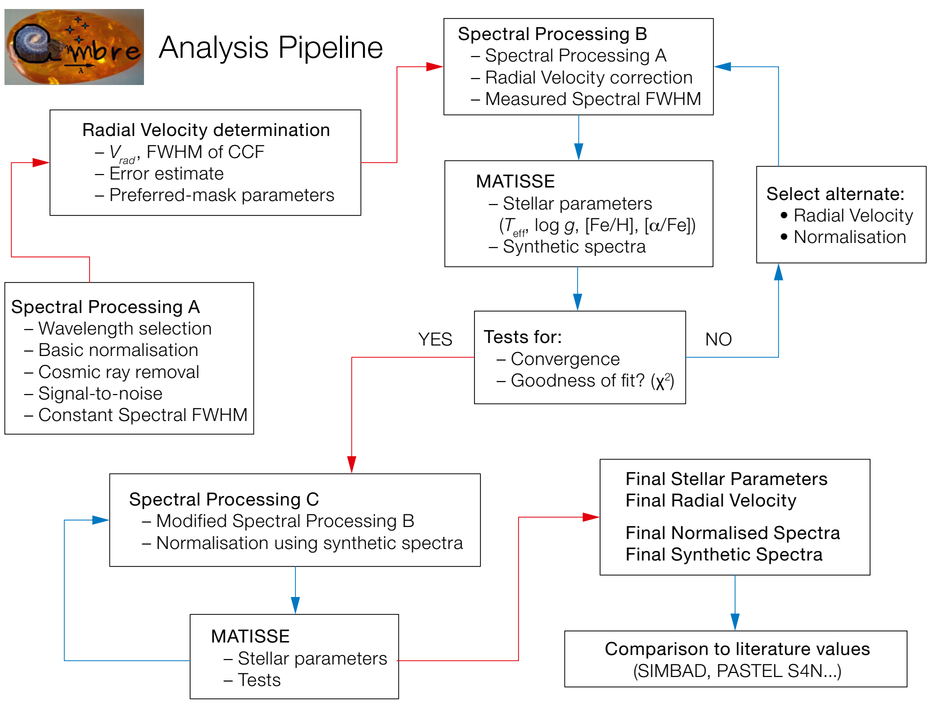


Figure 2. The AMBRE analysis pipeline as defined for the FEROS spectra and upon which the analysis of the archived spectra for the other three spectrographs is based (see Worley et al. [2012] for a detailed description).

together with their associated (internal and external) errors. Quality flags for these parameter estimates are also produced. We point out that external errors are estimated from the analyses of stellar atlases of well-known stars (the Sun, Procyon and Arcturus) and spectral libraries of reference samples (several hundreds of stars) found in the literature. Moreover, the analysis of the repeated observations by a given spectrograph allows us to estimate the internal errors of the adopted procedure (as an example, about 5% of the HARPS spectra correspond to the same stars — which may have been observed more than 20 times). Finally, typical total errors on the mean metallicity and the [α/Fe] ratios are around 0.1 dex and 0.05 dex, respectively, for spectra having SNR > ~ 25.

## Results: AMBRE parameterisation of FGKM-type stars

We have presently analysed about 230 000 spectra archived by ESO and collected with FEROS, HARPS and UVES (see Table 1) and fully parameterised about two thirds of them. We adopted several selection criteria to construct the final tables of stellar parameters. These criteria are based on the different quality flags produced by our procedure resulting in the rejection of the low SNR spectra, hot and/or fast-rotating stars, and/or the detection of non-standard spectra (binaries, chemically peculiar stars and so on), for which the AMBRE analysis pipeline has not been developed.

We finally provided ESO with the stellar parameters of ~ 6 500 FEROS spectra (corresponding to ~ 3 100 different stars),

Table 2. The list of AMBRE data products for FEROS spectra that have been ingested into the ESO archives (taken from Worley et al. [2012]). Similar tables have been produced for the other spectrographs.

| Keyword | Definition | Value range | Null value | Determination |
|---|---|---|---|---|
| DP_ID | ESO dataset identifier | | | |
| OBJECT | Object designation as read in ORIGFILE | | | |
| TARG_NAME | Target designation as read in ORIGFILE | | | |
| RAJ2000 | Telescope pointing (right ascension, J2000) | deg. | | |
| DEJ2000 | Telescope pointing (declination, J2000) | deg. | | |
| MJD_OBS | Start of observation date | Julian Day | | |
| EXPTIME | Total integration time | sec. | | |
| SNR | Signal-to-noise ratio as estimated by the pipeline | 0–∞ | NaN | |
| SNR_FLAG | Signal-to-noise ratio quality flag | C, R | | C = Crude estimate from SPA*, R = Refined estimate from SPC# |
| EXTREME_EMISSION_LINE_FLAG | Detection of extreme emission lines | T, F | | T = True: detection therefore no analysis carried out, F = False: no detection therefore analysis carried out |
| EMISSION_LINE_FLAG | Detection of some emission lines | T, F | | T = True: some emission lines detected but analysis carried out, F = False: no detection therefore analysis carried out |
| MEANFWHM_LINES | Mean FWHM of absorption lines around 4500 Å | 0–0.33 | NaN | FWHM measured from spectral features (mÅ) |
| MEANFWHM_LINES_FLAG | Flag on the mean FWHM | T, F | | T = True: *FWHM* > 0.33 or < 0.11. Default FWHM values used F = False: *FWHM* < 0.33, > 0.11 |
| VRAD | Stellar radial velocity | −500 to +500 | NaN | Units = km $s^{-1}$ |
| ERR_VRAD | Error on the radial velocity | 0–∞ | NaN | If $\sigma_{vrad}$ > 10, null value used for all stellar parameters. Units = km $s^{-1}$ |
| VRAD_CCF_FWHM | FWHM of the CCF between the spectrum and the binary mask | 0–∞ | NaN | Units = km $s^{-1}$ |
| VRAD_FLAG | Quality flag on the radial velocity analysis | 0, 1, 2, 3, 4, 5 | −99 | 0 = Excellent determination ... 5 = Poor determination |
| TEFF | Stellar effective temperature ($T_{eff}$) as estimated by the pipeline | 3000–7625 | NaN | Units = K. Null value used if $T_{eff}$ is outside accepted parameter limits or if the spectrum is rejected due to quality flags |
| ERR_INT_TEFF | Effective temperature internal error | 0–∞ | NaN | Units = K. Square root of quadrature sum of internal errors ($\sigma(T_{eff})_{int,snr}$, $\sigma(T_{eff})_{int,vrad}$ & $\sigma(T_{eff})_{int,norm}$) |
| ERR_EXT_TEFF | Effective temperature external error | 120 | NaN | Units = K. Maximum expected error due to external sources |
| LOG_G | Stellar surface gravity (log *g*) as estimated by the pipeline | 1–4.9 | NaN | Units = dex. Null value used if log *g* is outside accepted parameter limits or if the spectrum is rejected due to quality flags |
| ERR_INT_LOG_G | Surface gravity internal error | 0–∞ | NaN | Units=dex. Square root of quadrature sum of internal errors ($\sigma(\log g)_{int,snr}$, $\sigma(\log g)_{int,vrad}$ & $\sigma(\log g)_{int,norm}$) |
| ERR_EXT_LOG_G | Surface gravity external error | 0.2 | NaN | Units = dex. Maximum expected error due to external sources |
| M_H | Mean metallicity [M/H] as estimated by pipeline | 0-∞ | NaN | Units = dex. Null value used if [M/H] is outside accepted parameter limits or if the spectrum is rejected due to quality flags. |
| ERR_INT_M_H | Mean metallicity internal error | 0-∞ | NaN | Units = dex. Square root of quadrature sum of internal errors ($\sigma([M/H])_{int,snr}$, $\sigma([M/H])_{int,vrad}$ & $\sigma([M/H])_{int,norm}$) |
| ERR_EXT_M_H | Mean metallicity external error | 0.1 | NaN | Units = dex. Maximum expected error due to external sources |
| ALPHA | α-elements over iron enrichment ([α/Fe]) as estimated by pipeline | −0.4–0.4 | NaN | Units = dex. Null value used if [α/Fe] is outside accepted parameter limits or if the spectrum is rejected due to quality flags |
| ERR_INT_ALPHA | α-elements over iron enrichment internal error | 0–∞ | NaN | Units=dex. Square root of quadrature sum of internal errors ($\sigma([\alpha/Fe])_{int,snr}$, $\sigma([\alpha/Fe])_{int,vrad}$ & $\sigma([\alpha/Fe])_{int,norm}$) |
| ERR_EXT_ALPHA | α-elements over iron enrichment external error | 0.1 | NaN | Units = dex. Maximum expected error due to external sources |
| CHI2 | $chi^2$ of fit between observed and reconstructed synthetic spectrum for MATISSE parameters | 0–∞ | NaN | Goodness of fit between final normalised and final reconstructed spectra |
| CHI2_FLAG | Quality flag on fit between observed and reconstructed synthetic spectrum for MATISSE parameters | 0, 1, 2 | −99 | 0 = Good fit ... 2 = Poor fit |
| ORIGFILE | ESO filename of the original spectrum being analysed | | | |

Notes: * = Spectral Processing A; # = Spectral Processing C

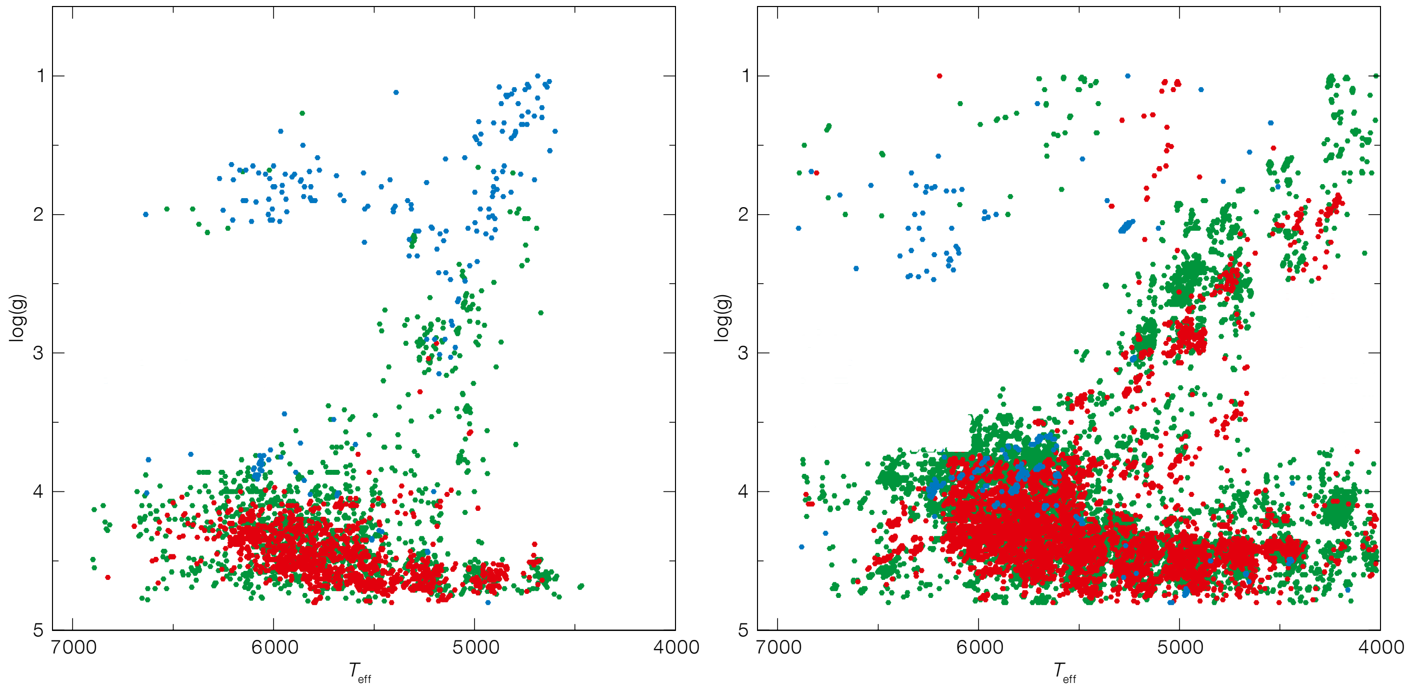


Figure 3. Hertzsprung–Russell diagrams of a subsample of the analysed spectra for FEROS (left panel, about 3600 spectra) and HARPS (right panel, ~ 75 000 spectra). Metal-poor stars ([M/H] < –1 dex) are plotted in blue, intermediate metallicity stars (–1 ≤ [M/H] < 0 dex) are in green and metal-rich stars ([M/H] ≥ 0 dex) in red.

~ 97 000 HARPS spectra (i.e. ~ 11 500 stars), and about 52 000 UVES spectra (around 25 000 stars). Radial velocities were determined for a larger sample of the spectra and are also part of the AMBRE products that have been sent to ESO. All these parameters have been ingested into the ESO archives (as Phase 3 Science Data Products) for storage and subsequent use by the scientific community. An example of all the derived data, their associated errors and different flags (32 entries in total) ingested into the ESO archives for a given spectrum can be seen in Table 2.

Finally, as an illustration of the AMBRE project results, in Figure 3 we show the Hertzsprung–Russell diagrams constructed from the derived stellar parameters of most of the FGKM-type slow-rotating stars analysed so far. These estimated stellar atmospheric parameters and chemical indices represent a huge amount of homogeneous and unique data that is ready to be exploited in terms of studies of stellar evolution and Galactic archaeology. We have already started some by-product analyses, such as the building of a catalogue of homogeneous projected rotational velocities of thousands of stars, the study of chromospheric indices in different types of stars, the mapping of the extinction of the interstellar medium, the heavy element content of stars in the Solar vicinity, and the separation of the thin/thick disc populations. Moreover, the AMBRE database is partly used as calibration data for the GES and Gaia surveys. We hope that the scientific community will make extensive use of the AMBRE database for a wealth of other astronomical projects.

## Acknowledgements

The AMBRE project has been financially supported by ESO, CNES, Observatoire de la Côte d'Azur (including the Mesocentre computing centre) and CNRS. We sincerely acknowledge L. Pasquini for initiating this project, M. Romaniello and J. Melnick for their help within ESO and F. Mignard for his long-lasting support. J.-C. Gazzano and Y. Vernisse are also thanked for their involvement in part of AMBRE.

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## Links

[1] AMBRE data release: http://archive.eso.org/cms/eso-archive-news/first-data-release-from-the-matisse-oca-eso-project-ambre.html