# Calibration of the General Stellar Parametrizer algorithms using ground-based observations

Definition of calibration data needs and candidate reference stars

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# Abstract

This document serves as a reference for the work package "Provide calibrations of training data" (GWP-S-811-20000) within the CU8 work package "Training data" (GWP-S-811). The purpose of that work package is to provide a basis for the calibration of the General Stellar Parametrizer algorithms (GSP-phot and GSP-spec). This document covers some aspects of the first three tasks of that work package. These are the first steps towards the two-fold aim of the calibrations work package: (1) establish an optimal list of *reference stars* that will be observed by Gaia to calibrate the GSP algorithms, (2) provide libraries of empirical spectra and related APs to improve synthetic spectra (*training spectra*). Some thoughts on the calibration procedures for the algorithms as well as the expected final accuracy of the AP determinations are included as well. A major part of this document is devoted to possible source catalogues for selection of AP reference stars. We focus on recent high-spectral-resolution surveys of bright field stars as well as faint open cluster stars. Globular clusters and large catalogues of calibrated spectrophotometric studies are briefly discussed as well.

# Document History

| Issue | Revision | Date | Author | Comment |
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# Acronyms

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

| **Acronym** | **Description** |
|---|---|
| AGB | Asymptotic Giant Branch (star) |
| AO | Announcement of Opportunity |
| AP | Astrophysical Parameter |
| DPAC | Data Processing and Analysis Consortium |
| DSC | Discrete Source Classification (Classifier) |
| ESO | European Southern Observatory |
| ESP | Extended Stellar Parametriser |
| GBOG | Ground-Based Observations for Gaia (DPAC) |
| GC | Globular Cluster |
| GOG | Gaia Object Generator |
| GSP | Generalised Star Parametrisation (Parametriser) |
| GSPphot | Generalised Stellar Parametriser PHOTometry |
| GSPspec | Generalised Stellar Parametriser SPECtroscopy |
| NOT | Nordic Optical Telescope |
| OC | Open Cluster |
| RAVE | RAdial Velocity Experiment |
| RVS | Radial Velocity Spectrometer |
| SDSS | Sloan Digital Sky Survey |
| SNR | Signal-to-Noise Ratio (also denoted SN and S/N) |

# Contents

# 1 Introduction

One of the goals of CU8 is to provide the astrophysical parameters (APs) – $T_{\rm eff}$ (effective temperature), log $g$ (surface gravity) and [M/H] (metallicity) – for those sources which the Discrete Source Classifier (DSC) identifies as single normal stars. The related parametrisation algorithms (General Stellar Parametrisers GSP-phot and GSP-spec) rely on templates which are built from grids of synthetic spectra. The calibration of these algorithms requires that Gaia obtains good data ("good" meaning high S/N, no overlap between spectra, etc.) for a set of stars representative of the whole parameter space, for which the APs are well known in advance. We refer to these stars hereafter as *AP reference stars*. Moreover, as the parametrisation is based on stellar atmosphere models which are not perfect, empirical spectra of calibration stars (hereafter referred to as *training spectra*) will be used to test and improve synthetic spectra.

The objective of work package GWP-S-811-20000 – "Provide calibrations of training data" – is the selection of the best stars that can be used as AP reference stars. This activity also deals with the compilation of data – spectra and astrophysical parameters – to be used for homogeneous and detailed characterization of the AP reference stars, and as training spectra. For the selection of AP reference stars and the search for useful data, we have to consider the resolution, spectral interval and magnitude ranges of the data Gaia will obtain with the BP/RP and RVS instruments (Blue/Red Photometer and Radial Velocity Spectrometer). We also have to take into account the final AP accuracy expected to be obtained by the algorithms.

In this document, we present the basic idea for a possible calibration procedure, which is to build a *primary* grid of AP reference stars, calibrated on *benchmark* stars, as well as a *secondary* grid, calibrated on the *primary* grid stars. The analysis will be based on existing data as a starting point, but new ground-based observations are mandatory.

# 2 Selection criteria for AP reference stars

## 2.1 Parameter space

### 2.1.1 Parameter ranges

For now, this document deals with cool stars – F,G,K stars (it might be extended to M stars in the future). Stars of these types will be the most numerous among the objects observed by Gaia, and they span a large range in stellar parameters such as metallicity and age. Therefore, their AP calibration will be crucial for achieving the mission goal of studying the structure and evolution of the Galaxy. We assume here that such stars are covered by the ranges in the parameters $T_{\rm eff}$, $\log g$ and [M/H] given in Table 1. The lower limit for $\log g$ corresponds to a rough estimate of the Eddington limit and depends slightly on $T_{\rm eff}$. The metallicity limits are preliminary and correspond to the metallicity range covered by available stellar catalogues. Stars with very low metallicity might require follow-up ground-based observations, or special treatment by the parametrization algorithms.

TABLE 1: Ranges in the parameters $T_{\rm eff}$, $\log g$ and [M/H] assumed to cover the regime of FGK stars. Ranges are given in the form [lower limit:upper limit]. The ranges in $(B-V)_0$ are for guidance only (and used for reference star selection below), and the lower and upper limits are set very generously.

| $T_{\rm eff}$ | log$T_{\rm eff}$ | $(B-V)_0$ | $\log g$ | [M/H] |
|---|---|---|---|---|
| [4000:5000] | [3.60:3.70] | [1.6:0.9] | [$-0.5$:5.0] | [$-3.0$:$+0.5$] |
| [5000:6000] | [3.70:3.78] | [0.9:0.6] | [$+0.0$:5.0] | [$-3.0$:$+0.5$] |
| [6000:7000] | [3.78:3.85] | [0.6:0.2] | [$+0.5$:5.0] | [$-3.0$:$+0.5$] |

### 2.1.2 Step sizes in parameter grid

Contrary to grids of synthetic spectra, grids of real stars cannot be built with exact regular steps in the three parameters. However, we can define a parameter grid and try to find stars which fall near the grid nodes. For setting the step sizes in this parameter grid we have to take into account several kinds of uncertainties:

1. The uncertainty inherent to the reference APs. We can distinguish stars whose APs rely on high resolution, high S/N spectroscopy, and low resolution spectroscopy or photometry.

2. The typical uncertainty of the APs determined in the Gaia data processing. They will mainly depend on the V (G) magnitude and instrumental effects (i.e. S/N) and details of the algorithms.

3. The required accuracy of the APs to achieve the Gaia science goals.

As the data processing algorithms are currently under development, definitive values for the uncertainties of the second kind are not yet available. Also, there is no official requirement for the AP accuracies ("as good as possible", item 3). Thus, for the purpose of this document, we try to consolidate different values which have been mentioned in various documents. These values are listed in Table 2, together with the values adopted here. In the "Proposal for the Gaia Data Processing" (April 2007, DPAC; aka "AO response document") , one can find two references to the expected accuracies of the astrophysical parameters, based on preliminary evaluations of parametrisation performance. In the Gaia Concept and Technology Study Report (July 2000), the section on "photometric requirements" states: "To be able to reconstruct Galactic formation history the distribution function of stellar abundances must be determined to $\sim$ 0.2 dex, while effective temperatures must be determined to $\sim$ 200 K". No requirements for the precision were found in the Mission Requirements Document, ESA Gaia Project (2006). Thus, we adopt the following goals for the precision of the parameter determination in this document: 2% for $T_{\text{eff}}$, 0.3 dex for log $g$, and 0.2 dex for the metallicity of most stars. Note that to achieve the stated accuracy for log $g$ at all magnitudes will presumably require the use of astrometric data.

In particular for studies of the Galactic halo, it will be important to derive the abundance of $\alpha$ elements, [$\alpha$/Fe], from Gaia data. The target precision for this parameter is around 0.2 dex. However, we leave the details concerning the calibration of this parameter to a forthcoming document. For the interstellar extinction, the "AO response document" gives values for the estimated precision of between 0.05 and 0.3 mag. The current document will not discuss the calibration of this parameter either.

TABLE 2: Values of required/expected precision for parameter determination found in various documents (AO response ... "AO response document" (April 2007); Concept Study ... Gaia Concept and Technology Study Report, July 2000). Values for log $g$ and [M/H] are in dex.

| Document | Section | pages | $T_{\text{eff}}$ | log $g$ | [M/H] |
|---|---|---|---|---|---|
| AO response | 2.3.1.2[a] | 41 | 1.5% | 0.25 | 0.1 |
| AO response | 5.5.5[b] | 163 (Fig. 40), 165 (Tab. 7) | 4.3% | 0.65 | 0.42 |
| Concept Study | 2.3.1 | 137 | 200 K | – | 0.2 |
| Adopted | – | – | 2% | 0.3 | 0.2 |

[a]Figure of merit evaluation of parametrisation performance, predicted errors for an F-type sub-giant star, G=17, solar metallicity

[b]Estimates of precision using a flexible nonlinear, multidimensional regression algorithm, for cool stars, G=15

## 2.2 Visual magnitudes of reference stars - bright vs. faint stars

The Gaia instruments will obtain observations of stars in different magnitude ranges. The Gaia photometers (providing data to be processed with GSP-phot) will saturate at around 10th magnitude. The RVS will provide data useful for AP determination (using GSP-spec) only for stars

| R=11500 | | R=5500 | |
|---|---|---|---|
| V | SNR | V | SNR |
| 8 | 420 | 12 | 100 |
| 9 | 260 | 13 | 55 |
| 10 | 160 | 14 | 25 |
| 11 | 95 | 15 | 12 |

TABLE 3: End-of-mission signal-to-noise ratios (SNR) per sample for RVS spectra, estimated for a K1V star for various V magnitudes (David Katz, 2007-11-14, priv. comm.).

brighter than about 11th to 13th magnitude (depending on resolution, see Table 3). Stars brighter than 6th magnitude will not be observed by Gaia. This results in two different sets of stars for AP calibration purposes, *bright stars* with $6 < V < 13$ and *faint stars* with $10 < V < 18$. Stars within both magnitude ranges will be considered within this document.

Note that BP/RP data will also be obtained for bright stars up to 6th magnitude, using “gates”, which will attenuate all stars to magnitudes fainter than 10 (presumably without loss in photometric precision) – see Hoeg & de Bruijne (2007). However, the exact properties of these gates are not decided, and therefore such data can not be simulated yet. Once the BP/RP instrument model for bright stars is known along with the expected AP accuracy, we will extend the magnitude range of AP reference stars for GSP-phot accordingly. Presumably we can use reference stars selected for GSP-spec for this purpose.

Selected calibration stars may fall outside the above magnitude limits, notably very bright stars (including $V < 6$). These will provide an indirect calibration of parametrization methods for Gaia via improvement in the theory of stellar atmospheres (see Sect. 3 below). We refer to such stars as *benchmark stars* and the corresponding ground-based data can contribute to the set of training spectra. Stars which fall within the magnitude limits (the reference stars) can be used for direct calibration of the parametrization methods after the launch of Gaia.

## 2.3 Position of reference stars – ecliptic-poles fields

Two fields of one square degree around the north and south ecliptic poles will be observed extensively during the commissioning and testing phase of the mission. As many as possible of the AP reference stars should be located within these fields. Thus, when selecting stars from existing catalogues or when planning new ground-based observations, the positions of the stars should be taken into account in addition to magnitudes and physical parameters. Also, a cross-correlation with the Ecliptic-poles star catalogue, which is being built up within CU3 by Altmann & Bastian (2008) has to be carried out.

# 3 Calibration procedure - a three-level approach

A simple combination of the values in Sect. 2.1 results in almost 10000 stars. Homogeneous observations at high spectral resolution and high signal-to-noise ratio do not exist for such a large number of stars, and cannot be obtained within the program of ground-based observations for Gaia. Even if this were possible, detailed spectrum analyses are neither available nor feasible before the launch of Gaia. Therefore we propose a *three-level approach* for calibration.

On the first level, we define a set of "benchmark stars". This consists of a small number (order of 10) of carefully selected, well-known bright stars. For the *benchmark stars*, a set of homogeneous data comprising very-high-resolution spectroscopy, spectrophotometry[1] and photometry will be obtained. These data will be analysed using the best available atmospheric models and input data. Standard analyses similar to those used for the *primary grid* (see next paragraph) will also be done in order to determine the necessary corrections for the results of such analyses. This work is done by the Gaia-SAM group and is related to Gaia work package GWP-S-811-10020 ("Expert Panel on Stellar Physics"). For more details we refer to the Gaia-SAM webpage[2] and the GaiaWiki page on Benchmark stars[3].

On the second level, we define a "primary grid" of reference stars, which will be studied in detail, based on high-resolution spectroscopy. The *primary grid* stars will be calibrated using the results obtained for the *benchmark stars*. Published spectroscopic data and standard analyses found in the literature will be used as far as available and will be complemented by new ground-based observations and new analyses. To link the *primary grid* to the *secondary grid* (see next paragraph), we also need spectrophotometric data with a similar resolution and photometric data in the same systems for all *primary grid* stars. We define the following steps in parameters for the *primary grid*: 7% for $T_{\rm eff}$, 1.0 dex for $\log g$, and 0.5 dex for the metallicity. This results in a managable number of 560 stars. The sources considered for selection of the *primary grid* stars are discussed in Sect. 4.1.

On the third level, we have the large grid of stars corresponding to our adopted values of parameter ranges and steps, which we call the "secondary grid". This grid will be used to calibrate the synthetic spectra used for algorithm training. The *secondary grid* itself will be calibrated using the results obtained for the *primary grid* stars. Stars will be selected from published analyses and calibrations of large surveys (10 000s of stars), like that of Allende Prieto et al. (2006). Ideally, the *primary grid* would be a subset of the *secondary grid*, but this may be difficult to realize (see currently considered sources for star selection in Sect. 4.2). The photometric or spectrophotometric data already available for these stars will be used to link the physical parameters to the synthetic spectra used for algorithm training. This requires to compute synthetic observables from the corresponding models.

[1] the term "spectrophotometry" is used as a synonym for low-resolution spectroscopy ($R \approx 2000 \dots 5000$)

[2] http://www.astro.uu.se/~ulrike/GaiaSAM/index.html

[3] http://www.rssd.esa.int/SA-general/Projects/GAIA/wiki/index.php?title=CU8:_Benchmark_Stars

# 4 Sources for AP reference stars

## 4.1 Primary grid

### 4.1.1 Field stars

TABLE 4: Source catalogues for selection of *primary grid* stars: type of data and references.

| Catalogue name | Catalogue description | $d_{max}$ [pc] | $R$ | S/N | [$\lambda_{min}$:$\lambda_{max}$] [nm] | References |
|---|---|---|---|---|---|---|
| PASTEL | Compilation, 450 references, 1990 and later | | | | | Soubiran et al. (in preparation), based on Cayrel de Strobel et al. (2001) |
| Taylor | Compilation, 340 references, 1960 and later | | | | | Taylor (1999), Taylor (2005) |
| Twarog spec | Compilation, see text | | | | | Twarog et al. (2007) |
| Gaia ESP cool | Compilation, see text | | | | | A. Lanzafame (priv. comm.) |
| Fuhrmann | Volume-limited | 25 | 60 000 | 200 | [420:750] | Fuhrmann (1998, 2000[a], 2004, 2008) |
| Luck & Heiter | Volume-limited dwarf[b], giant[c] and planetary host stars | [b]15, [c]100 | 60 000 | >150 | [475:685] | Luck & Heiter (2006, 2007) |
| Mishenina | Clump giants | 361 | 42 000 | 130–230 | [440:680] | Mishenina et al. (2006) |
| Ramírez | Nearby F–K stars | 150 | 45 000–120 000 | 100–600 | [450:780] | Ramírez et al. (2007) |
| S4N | Volume-limited | 14.5 | 50 000 | 150–600 | [362:921] | Allende Prieto et al. (2004) |
| SPOCS | Nearby F–K stars from planet search programs | 202 | 70 000 | 300 | [483:618] | Valenti & Fischer (2005); Takeda et al. (2007) |
| Takeda | Nearby F–K dwarfs and subgiants | 53 | 70 000 | 100–500 | [500:700] | Takeda et al. (2005) |

[a] `http://www.ing.iac.es/~klaus/`

Bright stars within the *primary grid* will be selected from various catalogues of analyses of field stars. A list of source catalogues under consideration is given in Tables 4 and 5. Abstracts

TABLE 5: Source catalogues for selection of *primary grid* stars: number of stars and parameter ranges. In addition to the data for the full catalogue, the number of stars and corresponding parameter ranges are listed for stars fainter than V=6 (RVS).

| Catalogue name | $V$ range | N | $T_{\rm eff}$ range | log $g$ range[a] | [M/H] range |
|---|---|---|---|---|---|
| PASTEL database | [0:15] | 4245 | [2710:32600] | [−1:5.4] | [−4.8:+1.1] |
| (FGK) | [0:15] | 3792 | [4000:7000] | [−1:5.1] | [−4.8:+0.8] |
| (RVS) | [6:15] | 2490 | [4000:7000] | [−1:5.1] | [−4.8:+0.6] |
| Taylor – dwarf stars | [0:14] | 1331 | [4050:6875] | [IV:V] | [−1.8:+0.5] |
| (RVS) | [6:14] | 1004 | [4050:6850] | [IV:V] | [−1.8:+0.5] |
| Twarog spec | [0:11] | 1801 | [4130:7375] | [3.0:5.1] | [−2.0:+0.6] |
| (RVS) | [6:11] | 1502 | [4130:7200] | [3.1:5.1] | [−2.0:+0.6] |
| Gaia ESP cool stars | [4:16] | 150 | [3800:6025] | — | — |
| Fuhrmann | [3:10] | 296 | [4800:6700] | [3.0:4.7] | [−2.1:+0.5] |
| (RVS) | [6:10] | 183 | [4800:6350] | [3.1:4.7] | [−2.1:+0.5] |
| Luck & Heiter (2006) | [0:10] | 217 | [4100:7300] | [3.1:5.0] | [−1.3:+0.6] |
| (RVS) | [6:10] | 108 | [4100:7100] | [3.7:5.0] | [−1.3:+0.6] |
| Luck & Heiter (2007) | [0: 8] | 298 | [4300:8000] | [1.7:4.4] | [−0.6:+0.3] |
| (RVS) | [6: 8] | 86 | [4600:8000] | [2.3:4.3] | [−0.6:+0.3] |
| Mishenina | [3: 9] | 177 | [4300:5500] | [1.5:3.2] | [−0.7:+0.3] |
| (RVS) | [6: 9] | 48 | [4600:5300] | [1.7:2.9] | [−0.6:+0.2] |
| Ramírez | [0:11] | 523 | [4300:6600] | [2.0:4.7] | [−1.5:+0.5] |
| (RVS) | [6:11] | 392 | [4700:6400] | [3.2:4.7] | [−1.5:+0.3] |
| S4N | [0: 7] | 118 | [4160:7650] | [1.9:4.9] | [−0.9:+0.5] |
| (RVS) | [6: 7] | 27 | [4420:5350] | [4.5:4.7] | [−0.9:+0.3] |
| SPOCS | [0:11] | 1039 | [4700:6600] | [3.1:5.1] | [−1.9:+0.5] |
| (RVS) | [6:11] | 901 | [4700:6600] | [3.1:5.1] | [−1.9:+0.5] |
| Takeda | [3: 7] | 160 | [5000:7000] | [3.2:4.9] | [−1.3:+0.5] |
| (RVS) | [6: 7] | 54 | [5100:6700] | [3.6:4.9] | [−1.3:+0.5] |

[a]or luminosity class range

of the references can be accessed from UH's ADS private library "AP reference stars"[4]. The PASTEL database contains all (non-compilation) catalogues listed in Table 4. The Taylor (2005) compilation contains Allende Prieto et al. (2004) and Fuhrmann (2004). The *Twarog spec* compilation is based on the SPOCS catalogue – Valenti & Fischer (2005) – and 25 other surveys (including those listed in Table 4 except for Fuhrmann 2000, 2008, Mishenina et al. 2006 and Ramírez et al. 2007). The parameter determinations for all stars in *Twarog spec* are transformed to the SPOCS $T_{\rm eff}$, log $g$, [M/H] scales. Quoting Twarog et al. (2007), "the majority of the final abundances should have uncertainties below 0.03 dex, and all should be below 0.06 dex". This compilation is used for the uvby$\beta$ metallicity calibration of the Twarog catalogue referred to in

[4]`http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=AP+reference+stars&libid=470e474905`

Sect. 4.2. The *Gaia ESP cool* compilation is a list of reference star candidates for calibration of the Gaia algorithm "Extended Stellar Parametrizer", more specifically the module dealing with cool, chromospherically active stars.

The individual catalogues listed below the compilations were selected according to the following criteria: (1) large number of stars studied, (2) spectroscopic analyses based on high-resolution spectra, (3) analyses of "good quality", i.e. based on well-known theoretical models with a critical review of methods and results included in the publication (4) spectral data available from the authors, for possible homogeneous reanalysis of the final AP reference star sample. The list of catalogues is preliminary and will be extended in the future, mainly towards lower gravities and lower metallicities. Detailed parameter-parameter diagrams and histograms for each catalogue will be presented in a forthcoming document.

### 4.1.2 Open cluster stars

Faint stars within the *primary grid* will be selected from open clusters (OCs). We start from clusters with known metallicity and select candidate AP reference stars covering the $T_{\rm eff}$ and $\log g$ grid parameters given in Sect. 3 from each cluster.

The clusters are selected following the procedure described below. The selected clusters are listed in Table 6 along with the cluster parameters metallicity, distance and age, as well as observability. They span a range in metallicity from $-0.4$ to $+0.4$ around solar. The clusters have well-known distances, reddening and ages.

The list of clusters is preliminary and will be extended and revised according to more recent metallicity determinations, e.g. Sestito et al. (2008); Bragaglia et al. (2008); Sestito et al. (2007, 2006); Randich et al. (2006). Additional criteria may also have to be taken into account, e.g. cluster radius (and therefore stellar density on the sky) to ensure optimal observing conditions.

**Cluster selection**

Starting point was the database for open clusters, WEBDA[5]. The section on cluster metallicities in WEBDA[6] contains lists of metallicity determinations or "FeH catalogues", by Twarog et al. (1997), Gratton (2000), Chen et al. (2003) and a list of "new values of the [Fe/H] iron abundances" with references to many works, including those contained in Friel (1995). These catalogues overlap in part. They were combined to a single catalogue by simply taking the values for clusters in common from the first catalogue in which these clusters appear, in the order given above. This results in a list of 136 clusters.

In addition, the web page of the "Open Clusters and Galactic Structure" project, cf. Dias et al.

[5] `http://www.univie.ac.at/webda/`
[6] `http://www.univie.ac.at/webda/description.html`

TABLE 6: Preliminary list of open clusters considered for selection of faint *primary grid* AP reference stars. The cluster names contain hyperlinks to the corresponding page in the on-line WEBDA database. Columns 2–4 give metallicity, distance and age. The "Observability" column gives observatories and periods where/when these clusters can be observed (odd ... April to September, even ... October to March).

| Name | [M/H] | d [pc] | t [Myr] | Observability | Reference for [M/H] |
|---|---|---|---|---|---|
| NGC 2506 | −0.4 | 3315 | 1648 | ESO/NOT even | Twarog et al. (1997) |
| NGC 2660 | −0.2 | 2859 | 1351 | ESO even | Twarog et al. (1997) |
| Melotte 111 | +0.0 | 86 | 522 | ESO/NOT odd/even | Gratton (2000) |
| IC 4756 | +0.0 | 415 | 674 | ESO/NOT odd | Twarog et al. (1997) |
| IC 2395 | +0.0 | 792 | 15 | ESO odd/even | Clariá et al. (2003) |
| NGC 2682 | +0.0 | 820 | 4093 | ESO/NOT even | Twarog et al. (1997) |
| NGC 6819 | +0.0 | 2188 | 2172 | NOT odd | Twarog et al. (1997) |
| Berkeley 18 | +0.0 | 4772 | 4271 | NOT even | Gratton (2000) |
| NGC 6791 | +0.2 | 4418 | 7850 | NOT odd | Twarog et al. (1997) |
| Melotte 25 | +0.2 | 42 | 708 | ESO/NOT even | Twarog et al. (1997) |
| NGC 6067 | +0.2 | 1676 | 95 | ESO odd | Twarog et al. (1997) |
| NGC 6253 | +0.4 | 1567 | 3949 | ESO odd | Gratton (2000) |

TABLE 7: Same as Table 6, in simple format (e.g. for presentations). d(nearby) $<$ 1 kpc $<$ d(far), t(young) $<$ 1 Gyr $<$ t(old).

| Name | [M/H] | Distance | Age | North/South |
|---|---|---|---|---|
| NGC 2506 | −0.4 | far | old | N/S |
| NGC 2660 | −0.2 | far | old | S |
| Melotte 111 | +0.0 | nearby | young | N/S |
| IC 4756 | +0.0 | nearby | young | N/S |
| IC 2395 | +0.0 | nearby | young | S |
| NGC 2682 | +0.0 | nearby | old | N/S |
| NGC 6819 | +0.0 | far | old | N |
| Berkeley 18 | +0.0 | far | old | N |
| NGC 6791 | +0.2 | far | old | N |
| Melotte 25 | +0.2 | nearby | young | N/S |
| NGC 6067 | +0.2 | far | young | S |
| NGC 6253 | +0.4 | far | old | S |

(2002), was consulted. Version 2.7 (27 Oct 2006) contains a list of metallicities for 143 clusters[7]. This list contains 19 clusters which are not in the WEBDA metallicity compilation.

[7] http://www.astro.iag.usp.br/~wilton/refsmetallicities.txt

Further, Paunzen & Netopil (2006) recently published a list of 72 open clusters with most accurately known parameters (age, reddening and distance). This list of “standard open clusters” and the list of clusters with metallicities have 40 clusters in common. None of these lie in one of the ecliptic pole fields.

Finally, from these 40 clusters, 12 clusters with roughly equispaced values of metallicity (step size 0.2 dex) and different distances and ages (to cover the desired magnitude range) were selected (nine of these are observable from the south, see Table 7).

We verified that the selected clusters are located in regions of the sky for which Gaia will obtain high-quality data, i.e. with a SNR of 100 or more. This SNR estimation is based on the calculations presented in Carrasco et al. (2006). The estimation will be repeated in the future with specific calculations using the Gaia Object Generator (GOG).

**Selection of stars from open clusters**

Candidate AP reference stars covering the $T_{\rm eff}$ and $\log g$ grid parameters given in Sect. 3 are selected from each of the selected clusters as follows. We base the selection on the UBV data compiled in WEBDA (because they are the most complete data available). The first step is to select stars according to $V$ and $B-V$ criteria, taking into account reddening: $9 \leq V \leq 18$ and $0.1 \leq (B-V)_0 \leq 1.7$. For each star, $T_{\rm eff}$ and $\log g$ is then estimated from the photometry: $T_{\rm eff}$ from $B-V$ (Castelli & Kurucz models), and $\log g$ from $V$, cluster distance, the bolometric correction (estimated from Castelli & Kurucz models), and $T_{\rm eff}$, assuming 1 solar mass and taking into account cluster reddening.

A grid in $T_{\rm eff}$ and $\log g$ is defined, with smaller step sizes than adopted for the *primary grid*. The $T_{\rm eff}$ values are 4000,4200,4400,4600,4800,5000,5400,5800,6200,6600,7000 K. The $\log g$ values range from 1.0 to 5.0 with a step of 0.5. Together with the metallicity range defined by the cluster selection, placing one star at each node would result in 495 stars. Next, for each grid node a star with estimated parameters deviating by at most 100 K in $T_{\rm eff}$ and 0.1 in $\log g$ is selected, if possible. For those clusters for which membership probability data is available, only stars with a probability larger than 60% are included (all stars with unknown membership probability are included as well).

This results in 15-40 stars per cluster, in total about 330 stars, which is about two thirds of the number covering the whole parameter space defined above. The coverage of the ($T_{\rm eff}$, $\log g$, [M/H]) space by the selected stars is shown in Fig. 1. One can see that the high-metallicity part of the *primary grid* is covered fairly well by these stars, except for a) stars at the hot edge, b) metal-poor stars at the cool edge and c) low values of gravity (corresponding to bright giants and supergiants, which probably fall outside the magnitude limit for most clusters). It remains to be investigated if these gaps can be filled by scrutinizing the whole list of 40 clusters with metallicity determinations and accurately known parameters. Otherwise, we have to look for reference stars in less well-studied open clusters or in catalogues of field stars (e.g. Sect. 4.2).

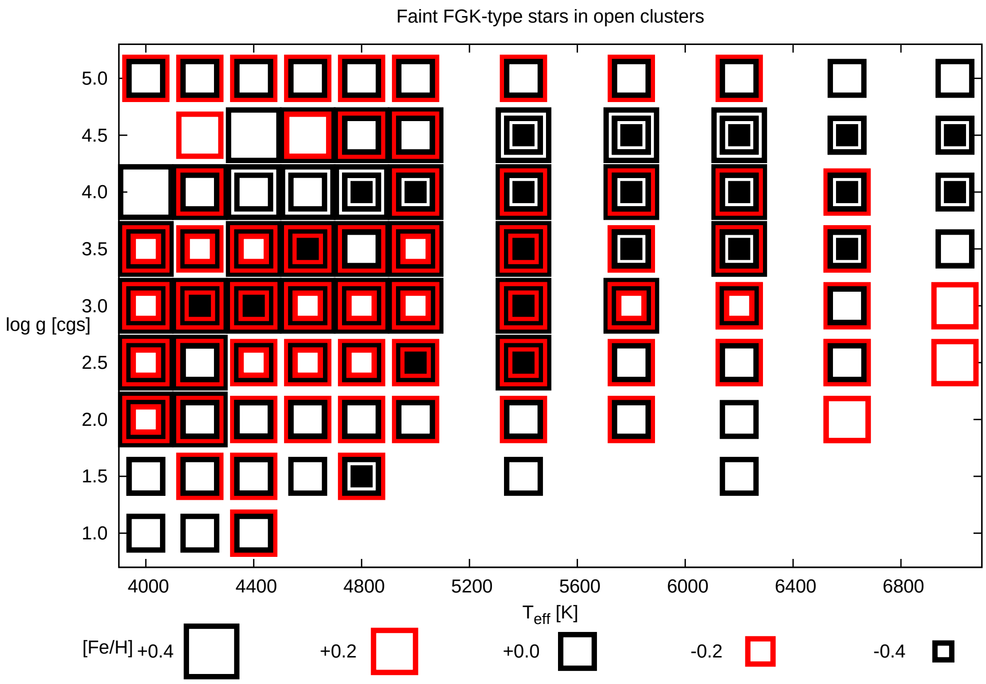


FIGURE 1: Coverage of astrophysical parameters by FGK type stars selected from the open clusters listed in Table 6 as outlined in Sect. 4.1.2.

Note that for each of the selected stars, accurate individual parameters ($T_{\rm eff}$, log $g$, [M/H]) have to be determined from the literature or from new analyses. A subset of these stars should be observed with high spectral resolution from one observatory (e.g. ESO), after having searched the archives for existing data. New, low-resolution spectra should be obtained with one and the same instrument (e.g. EFOSC2@NTT from ESO) for all stars, because we need a complete, homogeneous set of spectra. The issue of homogeneity is of higher concern for low resolution (flux calibrated) spectra than for high resolution spectra (Rosanna Sordo, priv. comm.).

### 4.1.3 Globular cluster stars

The selection of stars from globular clusters (GCs) will be done, if possible, in a similar way as for the open clusters. The details of the selection process will be described in a forthcoming version of this document or a separate document.

Globular clusters will be able to supplement the open cluster data as regards parameter-space coverage, in particular in terms of metallicity (extending down to [Fe/H] = $-2.4$), abundance ratios ($\alpha$-enhanced populations) and age (halo GCs are systematically older than disk OCs by several Gyr). It is clear that good coverage of the existing parameter space is highly desirable. The price to pay is the apparent faintness of GCs. NGC 6397, one of the GCs with the lowest distance modulus $(m-M)_0$ = 12.13 ±0.15 at $E(B-V)$ = 0.18, see Reid & Gizis (1998), has turnoff-point stars at apparent magnitudes close to 16.5 in $V$ (M92 is significantly fainter). At the low-metallicity end, additional physical effects could become interesting even at the precision Gaia is expected to achieve: the convective envelopes of cool stars become thinner and less massive which results in apparent abundance anomalies on the 0.2 dex level, see Korn et al. (2007). Targeting unevolved and evolved stars in GCs would allow us to assess the relationship between initial and apparent photospheric abundances for a variety of evolutionary phases (main sequence vs. red giant branch vs. horizontal branch vs. AGB), also in terms of mixing with nuclear burning products dredged up from the stellar core.

## 4.2 Secondary grid

TABLE 8: Source catalogues for selection of *secondary grid* stars: type of data and references.

| Catalogue name<br>Method | Data | References |
|---|---|---|
| SDSS spectroscopic study | SDSS spectra (381–910 nm, R=2000) and $ugriz$ photometry | Allende Prieto et al. (2006); Allende Prieto (2007) |
| Stellar parameters derived from fit to spectra and SDSS $g-r$ colors using Kurucz (1993) models and Hubeny & Lanz (2000) SYNSPEC code. | | |
| Twarog catalogue | uvby$\beta$ photometry | Twarog et al. (2007) |
| uvby$\beta$ metallicity calibration using the *Twarog spec* compilation (see Sect. 4.1). | | |
| RAVE stellar parameters | RAVE spectra (841–880 nm, R=7500) | Zwitter et al. (2008) |
| Stellar parameters derived from fit to spectra using synthetic spectra from Munari et al. (2005) based on “the latest generation of Kurucz models”. | | |
| Geneva-Copenhagen survey | uvby$\beta$ photometry | Holmberg et al. (2007) |
| uvby$\beta$ – $T_{\rm eff}$ calibration using $V-K$ colors and Di Benedetto (1998) calibration.<br>uvby$\beta$ – metallicity calibration using five works based on photometric $T_{\rm eff}$s. | | |
| Soubiran clump giants | ELODIE spectra (390–680 nm, R=42 000, S/N≈20) | Soubiran et al. (2008) |
| Stellar parameters derived from fit to spectra using TGMET code (Katz et al. 1998), based on template spectra observed with ELODIE. | | |

The *secondary grid* has yet to be defined. A first list of source catalogues for selection of *secondary grid* stars is given in Tables 8 and 9. Further sources are to be considered, e.g. Feltzing et al. (2001); Robinson et al. (2007). Abstracts of the references can be accessed from UH’s ADS private library “AP reference stars”[4].

TABLE 9: Source catalogues for selection of *secondary grid* stars: number of stars and parameter ranges.

| Catalogue name | $V$ range | N | $T_{\mathrm{eff}}$ range | log $g$ range[a] | [M/H] range |
|---|---|---|---|---|---|
| SDSS spectroscopic study | [14:20] | 94000[b] | [5000:8000] | [0.5:5.0] | [−4.8:+0.7] |
| Twarog catalogue | [ 3:14] | 35000[c] | [5000:6500] | [V:V] | [−1.0:+0.5] |
| RAVE stellar parameters | [ 9:12][d] | 21000 | [3400:27000] | [0:5] | [−2.0:+1.0] |
| Geneva-Copenhagen survey | [ 2:12] | 15000[e] | [4500:7000] | [V:V] | [−2.7:+0.8] |
| Soubiran clump giants | [ 6:10][f] | 523 | [4500:5700] | [1.0:4.5] | [−1.5:+0.3] |

[a]or luminosity class range
[b]73000 stars with $V \leq 18$
[c]32000 stars with $6 \leq V \leq 13$, 500 stars with $V \geq 10$
[d]$I$ magnitude range
[e]14500 stars with $V \geq 6$, 100 stars with $V \geq 10$
[f]Tycho2 $V_{\mathrm{T}}$ magnitude range

The parameter data for the SDSS study have been obtained from Carlos Allende Prieto (2008, priv. comm.). As an example, Fig. 2 shows the distribution of stars over V magnitude, $T_{\mathrm{eff}}$, log $g$ and [M/H] for this data set. The parameter data for the Geneva-Copenhagen survey are available from the CDS database[8]. The parameter data for the Twarog catalogue have been obtained from Bruce Twarog (2008, priv. comm.).

# 5 Conclusions

The calibration of the GSP-phot and GSP-spec algorithms is a challenging task. In this document, we have started to investigate the possibility of using grids of reference stars to test the algorithms as well as the synthetic spectra which are used as training data. Starting from the parameter regime of FGK stars, we have discussed selection criteria for reference stars, which include considerations of expected accuracy of the algorithms, magnitude ranges, and position on the sky. We have also outlined a possible approach for the calibration procedure. The final decision on the procedure has to be taken after consultation with algorithm providers and providers of synthetic spectra (discussions taking place in late-2008).

A major part of this document is devoted to surveying the possible source catalogues for selection of reference stars. In recent years, a number of studies using high-resolution spectra (resolutions on the order of 60 000) have resulted in precise measurements of astrophysical parameters of numerous nearby, bright stars ($V < 12$, on the order of 1000). The parameters covered are concentrated in the region of F to K dwarfs and the metallicities typically range from $-2$ dex to +0.5 dex. Fainter reference stars, suitable for calibration of the GSP-phot algo-

[8]`http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/475/519`

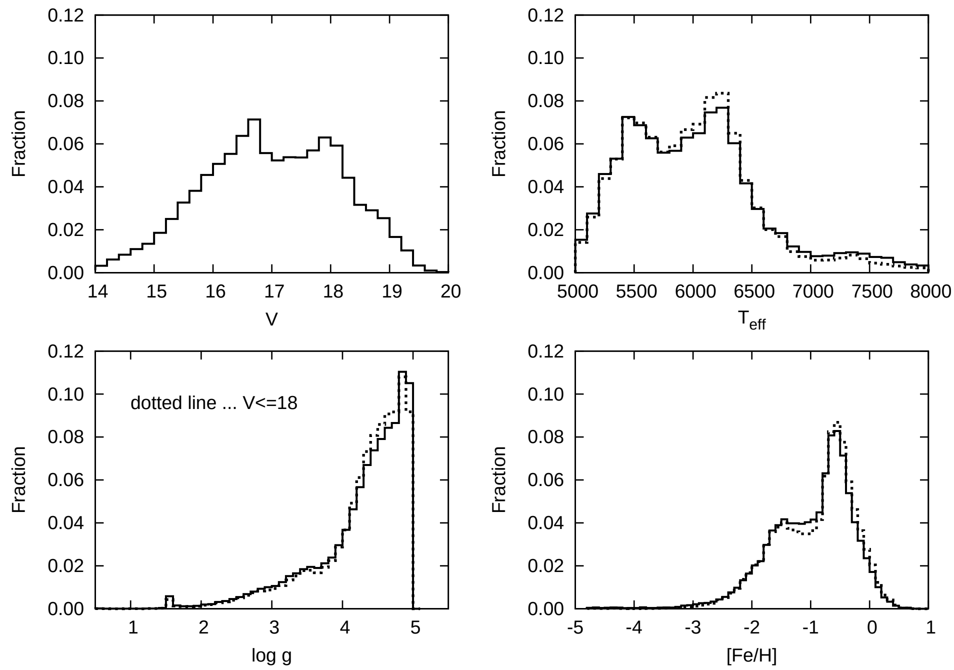


FIGURE 2: Distribution of stars over V magnitude, $T_{\mathrm{eff}}$, $\log g$ and [M/H] for SDSS data set (Allende Prieto et al. 2006; Allende Prieto 2007, Allende Prieto 2008, priv. comm.). Note that the distributions include all analysed spectra (about 90 000), and have not been corrected for duplicate observations of objects (a few thousand).

rithm, can be selected from open and globular clusters. Based on a survey of the data available in the WEBDA database, we have selected about 330 stars from 12 open clusters, which cover about two thirds of the parameter space of high-metallicity FGK stars. The metallicities of these stars are fairly well known from the cluster metallicities, but need to be confirmed, and further APs ($T_{\mathrm{eff}}$, $\log g$) remain to be verified. Globular cluster stars and stars from recently published large catalogues of calibrated spectrophotometric studies provide further promising sources for the selection of reference stars.

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