Proposition de recherche / Onderzoeksvoorstel

ORB Doctorant / KSB Doctoraatsstudent

2016

1. Etablissement scientifique fédéral / Federale wetenschappelijke instelling : Observatoire Royal de Belgique / Koninklijke Sterrenwacht van België
2. Département / Afdeling : Astronomie et Astrophysique / Astronomie en Astrofysica
3. Titre du projet / Titel van het project: **Development and application of an automated chemical composition measurement method of high-resolution stellar spectra including the Gaia-RVS domain.**
4. Date de mise en oeuvre du projet / Datum van de uitvoering van het project : 2016-2020
5. ORB Promoteur / KSB Promotor : Dr. A. Lobel (ORB / KSB) PhD Promoteur / PhD Promotor : Prof. Dr. A. Jorissen (ULB)

SUMMARY: The chemical composition of stellar atmospheres provides fundamental information about the evolutionary stages and ages of stars. This PhD proposal will develop a suite of computer codes for measuring the abundances of selected chemical elements from high-resolution optical and near-IR stellar spectra. The codes will venture beyond traditional equivalent line width analysis methods and determine fundamental astrophysical parameters (APs), including the elemental abundance values, from synthetic spectrum best fits to the detailed profiles of absorption lines. The proposed PhD research is innovative in that the codes will fully automatically determine the APs and commensurate abundance values. It will allow us to apply the codes to large collections of high-resolution stellar spectra observed in contemporary large spectroscopic surveys such as the Gaia-RVS and Gaia ESO Survey. The codes development and testing will employ a large sample of ~1500 BAFGK stars observed over the past 6 years with the Mercator-HERMES spectrograph in a scientific collaboration program with the Univ. of Leuven. The HERMES spectra will be used for a thorough investigation of stellar rotation effects on the expected enhancements of C, N, and O abundances in rapid-rotating A- and B-type field stars. The automatic abundance measurement codes will be used for determining accurate abundance values of several iron group elements (i.e., Fe, Ti, Ni) in a large number of FGK stars with the Galactocentric radius, also called the observed (local) Galactic metallicity gradient. The new computer codes will be very valuable for the advanced scientific exploitation of very large spectroscopic datasets (i.e., from Gaia & GES) which will become available in the public domain over the next 4 years, and in future spectroscopic surveys.

PROBLEM: Detailed abundance values of chemical elements in stellar atmospheres are crucial for unravelling the life cycles of stars from star formation to death. These values combined with the fundamental stellar parameters of mass (M_*), effective temperature (T_{eff}), and atmospheric acceleration (log$g$) are of central importance in astrophysics research investigating the physics of stellar atmospheres, the dynamics of winds, and the properties of circumstellar environments. They provide indispensable information about the formation and internal Galactic structure. When combined with space-velocities and distances to stars the atmospheric abundances provide essential information about the formation time-scales of the major constituents of our Galaxy.

Radial velocity measurements of stellar spectra can often be performed model independently. They only require selected lists of lines (or masks) for the spectral cross-correlation algorithms. Detailed abundance measurements, on the other hand, require profound knowledge of the physics of stellar atmospheres and of radiative transfer calculations for the theoretical modelling of stellar spectra. For this purpose astrophysicists have developed advanced computer codes that calculate the thermo-dynamical conditions in stellar atmospheres for a large variety of stars. The APs are computed with sophisticated codes that solve the transport of photons from the base of the atmosphere to their escape to Earth. The lines spectrum can be fit in exquisite detail for a unique combination of APs, which also determines the detailed element abundance values and projected rotation velocity of the stars.

In classical abundance measurements the (selected) spectral lines are individually investigated. After normalization to the stellar continuum flux level the wavelength position and "equivalent width" (EW) of each line (a measure for relative flux absorbed by the atomic transition) are recorded and repeated for large numbers of lines (~100). Next, the lists of measured line values are matched to theoretical values computed with the transfer codes for determining the best fitting AP values. This line measurement procedure, however, is very time-consuming and requires human (manual) interventions, which are often prone to errors.

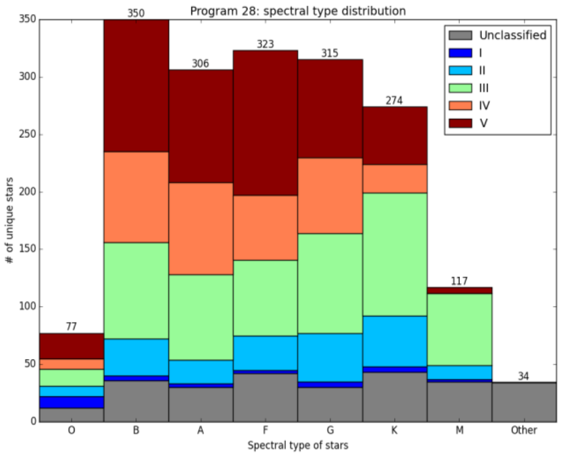

Figure 1: High-resolution spectra of BAFGK-stars we observed for Mercator-HERMES Program 28 (P28) in 2009 - 2015. The spectra will be used for this PhD research proposal. The numbers of observed stars are marked. Five luminosity classes I-V (covering a wide range of stellar surface gravity values) are shown in different colors.

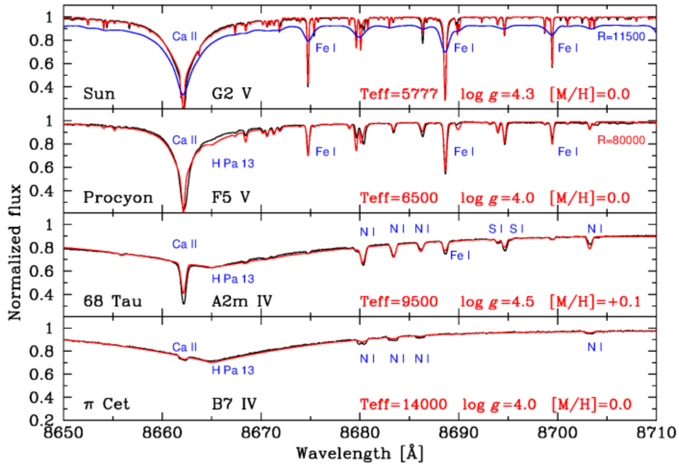

***Figure 2:** HERMES P28 spectra observed in the Gaia-RVS domain (black lines) of the Sun (G2), Procyon (F5), 68 Tau (A2), and π Cet (B7). Our best spectrum synthesis fits are shown in red for T_{eff}, logg, and [M/H]. The blue line shows the spectrum with Gaia-RVS resolution. Important diagnostic Ca II, H I, N I, S I, and Fe I lines are also marked.*

This problem severely limits the capacity by which extensive collections of stellar spectra can be analyzed for APs and chemical composition. Traditional spectrum analyses are therefore mostly limited to determining abundance values of a rather small number (<100) of representative stars for a given class under investigation.

The advent of multi-fibre spectroscopic observations over the past decade has dramatically increased the number of high-resolution spectra that can provide important element abundance information. For example, the Gaia ESO Survey (2011-2017) will observe about one hundred thousand (10^5) high-resolution optical VLT spectra of stars of all populations in the Galaxy. The ESA-Gaia astrometry mission (2013-2018) is a sky scanning satellite that will observe the medium-resolution near-IR (RVS) spectra of ~2 million stars ($G_{RVS} < 11^m$) with SNR > 80. Gaia is expected to measure distances to better than 10% of 220 million stars to 25 kpc. The astrophysical exploitation of the spectral datasets collected by these telescopes is a real challenge for classical abundance measurement methods. This PhD proposal will develop an advanced spectrum analysis method that alleviates the lingering problem of (slow) manual interventions. The research will implement a fully automated abundance measurement technique for handling extensive datasets of (homogeneously) observed stellar spectra.

METHODS: We will replace the classical EW measurement method with synthetic spectrum calculations of the detailed profiles of selected ('diagnostic') lines. Our method will initially compute a large and refined grid of detailed theoretical optical and near-IR spectra covering the AP ranges of late B-, A- & FGK-type stars (4 kK < T_{eff} < 15 kK, 0.0 < log*g* < 5.0, -3.0 < [M/H] < +1.0). The spectra will be computed with the LTE `Scanspec` code developed over the past decade by the ROB Promoter [1]. The thermal structures of the atmosphere models will be converged with the `ATLAS9` code using the ROB's HPC infrastructure. Both codes have been extensively tested and applied in recent years for the development of the online SpectroWeb database, and for the involvement of the ROB Promoter in detailed abundance analyses of VLT-UVES GES spectra of A-type stars [2]. For the APs and abundance determinations this PhD project will implement an automated template spectrum normalization procedure and employ a fast steepest-descent mean $\chi 2$-minimization method using carefully selected sets of unblen-

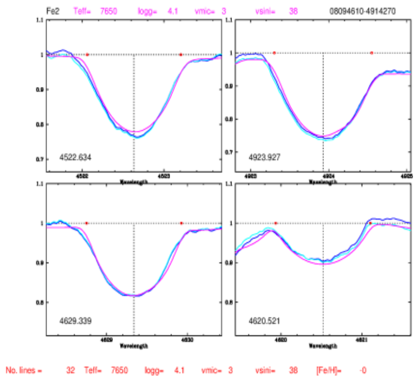

Figure 3: Synthetic spectrum best fits (cyan lines) to the detailed shapes of 4 Fe II lines observed in an A dwarf (blue). We compute the best stellar parameters (red) from 32 diagnostic Fe I and Fe II lines.

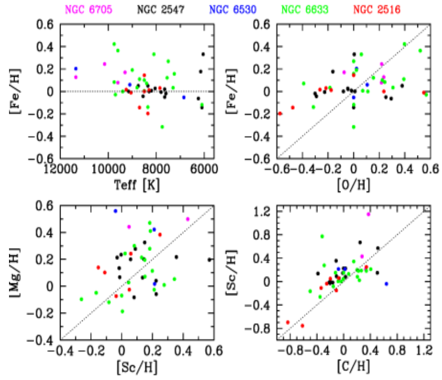

Figure 4: Chemical abundance values of various elements (Fe, Mg, O, Sc, & C are shown) we compute for ~40 stars with 6 kK ≤ Teff ≤ 12 kK using detailed LTE synthesis calculations of their optical GES spectra.

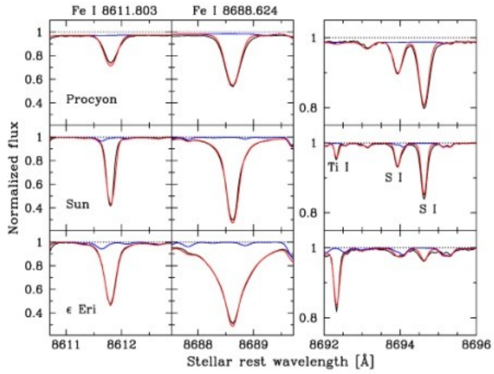

Figure 5: Best synthetic spectrum fits (red) to lines of Fe I, Ti I, and SI observed in Procyon (F5), the Sun (G2), and ε Eri (K2) with HERMES (black lines) in the Gaia-RVS domain. The blue spectra are computed without these transitions.

ded Fe I and Fe II lines. The APs and element abundance values will be iteratively determined by systematically varying the APs to compute the best fit to the observed line profiles. Figure 1 shows an overview of HERMES high-resolution spectra (R=85,000) observed by the ROB Promoter for Program 28 (P28). The sample contains ~1500 BAFGK-type (field) stars observed with sufficient SNR (>150) for measuring element abundances. The HERMES sample also contains a substantial fraction of bright stars with published APs and [Fe/H]-values that will be used to validate the results of the automatic APs and abundance measurement codes. Figure 2 shows some examples of best fits with `ATLAS9` & `Scanspec` (red lines) to HERMES spectra of bright BAFG stars (black lines) observed in the Gaia-RVS domain [3].

Figure 3 shows plots of detailed profile fits to 4 Fe II lines observed for the GES in A-type star 08094610-4914270 of NGC 2547. The detailed line profile best fits (magenta lines) require the (re-)normalization (cyan) of the observed spectrum (blue) using synthetic templates. Figure 4 shows the abundance values of 5 elements (Fe, Mg, O, Sc, & C) observed in ~40 A-type stars of 5 open clusters (marked with colours.) The values are iteratively determined from detailed best fits to unblended Fe I & Fe II, C I, O I, Sc II, and Mg I & Mg II lines. The smallest step size for the abundance iterations is 0.01 dex. A substantial number of stars reveal overabundances of [Mg/H] to ~< 0.6 dex and show that [Mg/H] weakly correlates with [Sc/H] in these A-type stars. The quality of the atomic input data in the theoretical spectra are evaluated in the Brain.be BRASS networking project coordinated by the ROB Promoter [4].

Expected Science Results: The PhD project will investigate two important questions regarding the statistical distribution of detailed element abundances with stellar rotation velocities and with stellar distances. The development and application of automated abundance measurements to the HERMES P28 sample with several hundreds of A- and B-type field stars will allow us to compile and investigate a (more) complete "Hunter-diagram". The diagram shows [N/H] vs. projected star rotation velocities ($v$sin$i$) and is important for studying possible (dynamical) effects of (rapid) stellar rotation on the abundance of CNO-cycle processed elements in stellar atmospheres [5]. Inefficient rotational mixing can for example not explain the slow rotators with N-enriched surface abundances (Box 2 in Fig. 6). 5 N I lines (see Fig. 2) are being observed in Gaia-RVS spectra for hundreds of thousands A- & B-stars. Our extensive HERMES datasets (Fig. 1) and the upcoming Gaia data releases will allow us to remove any biases in the analysis of the diagram currently due to low-number statistics.

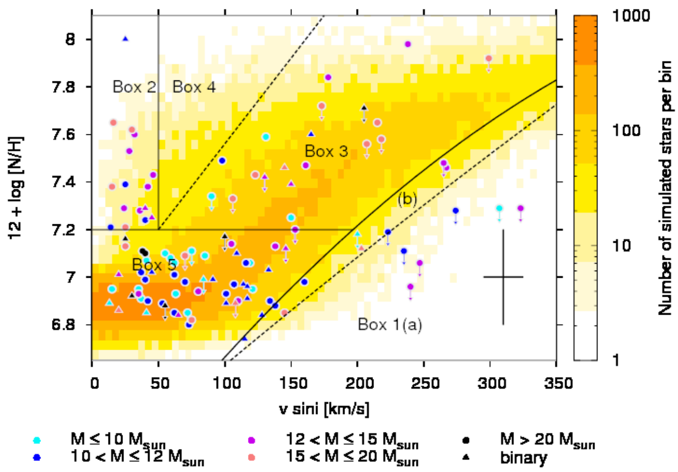

***Figure 6:** This PhD proposal will allow us to investigate possible dependences of surface nitrogen abundance [N/H] on stellar rotation velocity (v sini) in several hundreds of A- and B-type stars we observed with Mercator-HERMES.*

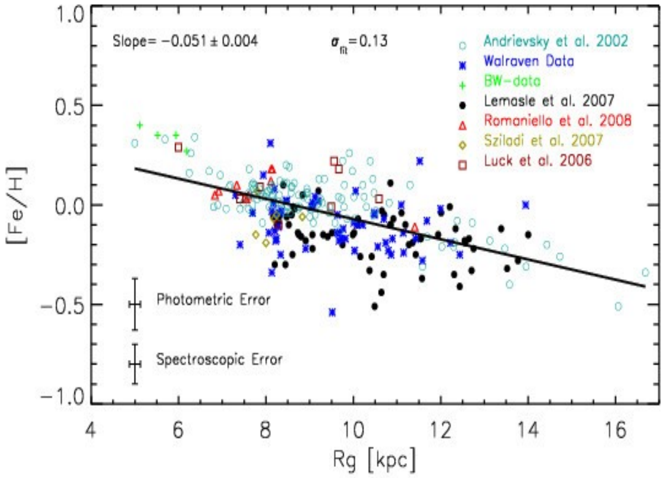

***Figure 7:** This PhD proposal will allow us to investigate the Galactic metallicity gradient using several hundreds of HERMES FGK spectra. The gradient is reported in studies of iron abundances [Fe/H] with radial Galactocentric distance (Rg).*

This PhD proposal will investigate the (local) “Galactic metallicity gradient” observed over the past decade in several studies of atmospheric iron abundances with distance to the Galactic center. The steady radial decrease of [Fe/H] has been reported in small samples of cool stars (Fig. 7) [6]. The research is important for the chemical evolution of the thin disc of the Galaxy, i.e. did the Galactic halo form before the thin disc? The project will allow automatic and accurate [Fe/H] measurements using HERMES P28 spectra of several hundreds of dwarf and giant FGK field stars. Note that 14 Fe I & 10 Ti I lines (see Fig. 5) are currently being observed in Gaia-RVS spectra (G_{RVS}<11^m) of ~2 million (A)FGK-stars at d<25 kpc. The Gaia catalog will offer accurate stellar positions and distances for G < 20^m. Our extensive HERMES datasets and the upcoming Gaia-RVS data releases will allow us to investigate the radial metallicity gradient in a large statistical sample, together with an analysis of the vertical abundance gradient.

PhD Workplan:

First year (in parallel):

- Compute large grid of high-resolution optical and near-IR synthetic spectra using the `ATLAS9` & `Scanspec` codes.
- Perform a quality study of the HERMES P28 dataset for selecting all spectra of BAFGK stars useful for detailed synthetic spectrum modeling. Include an evaluation of the signal-to-noise quality in the Gaia-RVS domain. Compile hot star radial velocity masks.
- Develop algorithms for automated measurements of APs and element abundances.

Second year:

- Implement, test, and validate the codes using HERMES spectra of bright reference stars.
- Study the literature on the Hunter diagram and the Galactic metallicity gradient.
- Write PhD dissertation chapters summarizing the adopted coding methods, scientific relevance of their application, and the results analysis strategy.

Third year:

- Apply the suite of codes to separate sets of HERMES spectra of B, A, F, G, and K-stars, and calculate APs and detailed abundances of selected elements (i.e., Fe, Ti, N, O).
- Evaluate APs & abundance results. Interpret results and publish as they are produced.

Fourth year:

- Involve in automated abundance analysis of the Gaia-RVS/GES data releases with the new suite of codes. Focus on timely completion of the PhD dissertation.

References:

[1] Lobel A. 2011, Canadian Journal Physics 89, 395.

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[3] Lobel A. 2011, Journal of Physics Conf. Series 328, 012027.

[4] Lobel A., Royer P., and Martayan C. 2015, The Belgian Repository of fundamental Atomic data and Stellar Spectra (BRASS) at www.belspo.be/belspo/fedra/proj.asp?l=en&COD=BR%2F143%2FA2%2FBRASS

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[6] Pedicelli S., Bono G., Lemasle B., et al. 2009, Astronomy & Astrophysics, 504, 81.