D3.6 Materials in Science Applications of Stellar Spectroscopy

EXOHOST

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Anna Aret	Project Coordinator	Reviewed, approved	28.10.2025

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1 Executive Summary

This deliverable presents the training materials created within the EXOHOST project, which has successfully enhanced the capacity for spectral characterisation of exoplanet host stars and related stellar types at the University of Tartu (UTARTU). The materials support both the use of spectral fitting software and the processing and analysis of spectral datasets.

Training was implemented through workshops, expert visits, secondments, and participation in international schools. A wide range of software tools was adopted and further developed, with accompanying tutorials and documentation created to ensure their usability. To facilitate access, a software matrix was compiled, providing links to codes, tutorials, and references.

All training resources produced within EXOHOST are systematically shared via the project website, Zenodo, GitHub, and other appropriate platforms. These efforts have significantly improved UTARTU's capability to conduct high-quality spectroscopic analyses, positioning the group as a stronger and more competitive partner in the field of stellar and exoplanetary research. The openly accessible resources also support the wider astrophysical community.

2 Introduction

The EXOHOST project addresses a critical need for modernisation of the stellar spectroscopy skillset at the University of Tartu (UTARTU). While the group has long-standing expertise in observational astrophysics, there was a clear need to strengthen its capacity in advanced methods for the processing, modelling, and analysis of stellar spectra. Through collaboration with partners OEAW and UU, EXOHOST implemented a programme of knowledge transfer designed to close this gap and enable UTARTU to fully exploit new opportunities, particularly those offered by the new UTARTU echelle spectrograph.

This deliverable focuses on one key element of that programme: the creation and sharing of training materials. These resources were developed through workshops, expert visits, and secondments, covering topics from the fundamentals of stellar spectroscopy to the use of modern analysis pipelines and spectral fitting tools. Complementary training was also obtained at international schools, which contributed to capacity building, even if their materials cannot be redistributed.

In addition to training events, EXOHOST supported the adoption and development of a broad suite of software for spectral analysis. Newly developed and amended tools were accompanied by tutorials and documentation, ensuring that their use can become a sustainable part of the UTARTU research culture. The project also produced a software matrix to facilitate access to codes, tutorials, and references for both project partners and the wider community.

By systematically sharing its outputs via the project website, GitHub, Zenodo, and other appropriate platforms, EXOHOST ensures that the training materials and tools are openly available for reuse, maximising their long-term scientific impact.

3 Training activities

Knowledge transfer activities started immediately after the beginning of the grant and were carried out through joint workshops, expert visits, and secondments, providing training on topics ranging from state-of-the-art stellar spectroscopy methods and tools to practical applications and the development of new software. These activities resulted in a variety of training materials, which are systematically shared via the project website, GitHub, and Zenodo. Materials produced outside EXOHOST, such as those obtained through participation in international summer and winter schools, have also contributed to capacity building, though their redistribution is subject to the policies of the organising institutions.

3.1 EXOHOST Stellar Spectroscopy Workshop

The Stellar Spectroscopy Workshop was organised as an intensive training event on stellar spectroscopy and data analysis, introducing participants to the basics of the field with a focus on intermediate-mass main-sequence stars (F-, A- and late B-type stars). Participants obtained practical information on methods and codes directly applicable to the analysis of stellar spectra, with substantial time devoted to hands-on sessions for learning the basic usage of selected tools. Several follow-up workshops were organised, helping to connect the stellar spectroscopy workshop with actual science by covering topics like proposal writing.

The Stellar Spectroscopy Workshop was held at Tartu Observatory, Tõravere, Estonia, on 27-28 September 2023. It was open to the whole research community and attracted over 90 participants from all over the world (both online and on-site).

Extensive training materials were produced in the result of the workshop, which have been uploaded to the file exchange platform Owncloud and are accessible to the general public from the EXOHOST website under the Stellar Spectroscopy Workshop event page (https://exohost.ut.ee/spectroscopy-workshop).

Detailed description of the workshop and its results is provided in the D3.1 Stellar Spectroscopy Workshop Summary Notes.

3.2 Ad-hoc Training

In addition to the workshop, targeted ad-hoc training was provided through expert visits and on-demand support within the UTARTU group. This training addressed specific technical challenges and contributed to the development of customised tools and workflows. For example, expert visits by Nikolai Piskunov (UU) focused on pipeline development, while Luca Fossati (OEAW) provided an online tutorial on artificial flat-fielding. While these activities did not result in standalone training packages for public release, they were crucial for consolidating the group’s skills and directly supported the development of EXOHOST training materials.

3.3 Participation in International Summer/Winter Schools

Members of the UTARTU group participated in several international summer and winter schools, with their attendance supported by EXOHOST. These events provided training on advanced methods in stellar astrophysics and exoplanetary science, contributing to capacity building by exposing early-career researchers to state-of-the-art techniques and fostering contacts with the wider community. The training materials from these external events are subject to the policies of the organising institutions and therefore cannot be redistributed through EXOHOST channels, but the knowledge acquired has been integrated into the group's practice and contributes to the development of EXOHOST's own open training resources.

3.3.1 Summer/Winter Schools attended

School	Dates	Location	Attended
Summer School for AstroStatistics	19.06-23.06.2023	Heraklion, Greece	Heleri Ramler
ARES III School: Hot planets with Radius < 4 Rearth, classic retrieval versus Machine Learning techniques	11.09-17.09.2023	Biarritz, France	Alexandra Lehtmets
From stars to planets in the space-based photometry era	28.01-03.02.2024	Saas-Fee, Switzerland	Veronika Mitrokhina, Alexandra Lehtmets, Kertu Metsoja
The Physics of the Star Formation	12.02-23.02.2024	Les Houches, France	Veronika Mitrokhina
6th Scientific Writing for Young Astronomers	05.05-09.05.2025	Sintra, Portugal	Veronika Mitrokhina
5th Advanced School on Exoplanetary Science	26.05-30.05.2025	Salerno, Italy	Alexandra Lehtmets
ARES IV School: Transits, eclipses, and phase curves for probing the atmospheres of hot gaseous planets	08.06-14.06.2025	Fréjus, France	Alexandra Lehtmets
Summer School for AstroStatistics	16.06-20.06.2025	Heraklion, Greece	Alexandra Lehtmets
2nd ChETEC-INFRA Observational School (ChINOS)	20.07-26.07.2025	Prague, Czechia	Vitalii Checha
Spectroscopic data analysis with iSpec	02.09-05.09.2025	Wrocław, Poland	Veronika Mitrokhina

4 Adopted Software Tools

Software plays a central role in the processing and analysis of stellar spectra, and the EXOHOST project has significantly expanded the toolkit available to the UTARTU group. This section presents the software tools that were **developed or amended with EXOHOST support** with instructions and tutorials to ensure their effective use and integration into training activities.

The section also introduces a **software matrix** consolidating an overview of all tools adopted during the project, including EXOHOST-developed software, existing codes amended with project support, publicly available open software, and private software accessed through collaborations. An excerpt of the matrix is included in Appendix A, while the complete and continuously updated version is available on the EXOHOST website https://exohost.ut.ee/software-matrix/.

All software and related materials are systematically shared through the project website, GitHub, and other suitable platforms to ensure both immediate usability and long-term availability. Beyond serving the needs of the UTARTU group, these resources are designed to benefit the broader community by enabling the reuse of tools and training materials.

4.1 Tools Developed or Amended with EXOHOST Support

4.1.1 Spectroscopy-Toolbox

A Python-based package for data diagnostics, developing linelists, and other utilities, with the option to extend functionality as needed. It was developed as part of the data reduction pipeline for the Tartu Observatory Fibre-Fed Echelle Spectrograph. The toolbox is publicly available via GitHub and is accompanied by documentation and tutorials.

Repository https://github.com/Sandipan-Borthakur/spectroscopy-toolbox

Tutorial https://github.com/Sandipan-Borthakur/spectroscopy-toolbox/blob/master/README.md

Publication Borthakur *et al.* In preparation

4.1.2 sponchpop

A synthetic planet population code, modular and designed for easy extension. It was amended during EXOHOST and will be made publicly available upon release, accompanied by documentation and tutorials.

Publication Kama *et al.* In preparation

4.1.3 ZMCwrap

A Python wrapper around the Zeeman spectral synthesis code that uses a Markov Chain Monte Carlo approach (via emcee) to estimate stellar parameters and chemical abundances from observed spectra. Initial testbed solution by coupling an off-the-shelf Python library for Markov Chain Monte Carlo methods with the Zeeman stellar spectral synthesis code was further developed, tested, and validated with assistance from OEAW and UU. ZMCwrap is open source, with usage instructions and tutorials available online. The software has become a sustainable standard tool for current and future members of the team.

Testing report D3.5 Validated Bayesian code for stellar spectral fitting

Repository https://github.com/folsomcp/ZMCwrap

Tutorial https://github.com/folsomcp/ZMCwrap/blob/main/README.md

Publication Folsom *et al.* In preparation

4.1.4 SpecpolFlow

A set of tools for analysing reduced spectroscopic and spectropolarimetric data. Contains a set of Python functions and classes, and also a command-line interface. Includes tools for coadding spectra, calculating radial velocities, calculating line bisectors, calculating LSD profiles, generating LSD masks, and reading and processing VALD line lists. The version currently in beta adds tools for calculating equivalent widths, plotting VALD line lists. The package is open source and comes with documentation and tutorials.

Repository https://github.com/folsomcp/specpolFlow

Tutorial https://folsomcp.github.io/specpolFlow/

Publications Folsom, Erba, *et al.*, 2025. Journal of Open Source Software, 10(111), 7891 https://doi.org/10.21105/joss.07891

Folsom, Erba, *et al*., 2025. Zenodo https://doi.org/10.5281/zenodo.15875239

4.1.5 normPlot

A tool for continuum normalisation of echelle spectra, usable as a stand-alone package or as part of SpecpolFlow, or as a stand-alone tool. Developed further during EXOHOST, it is publicly available with tutorials and documentation.

Repository https://github.com/folsomcp/normPlot

Tutorial https://folsomcp.github.io/specpolFlow/Tutorials/2-Normalizing_Tutorial.html

Publication Folsom *et al*. 2025. Zenodo https://doi.org/10.5281/zenodo.15871787

4.1.6 TOFFES-DRP

TOFFES-DRP is the data reduction pipeline for the Tartu Observatory Fibre-Fed Echelle Spectrograph based on the PyReduce package. PyReduce is a Python port of the IDL-based REDUCE package for echelle data reduction. The package was further developed and validated within EXOHOST and is openly available with documentation and tutorials.

Repository https://github.com/Sandipan-Borthakur/TOFFES-DRP

Tutorial https://pyreduce-astro.readthedocs.io/en/latest/index.html

Publications Borthakur *et al*. In preparation

Piskunov & Valenti 2002, A&A 385,1095

Piskunov et al. 2021, A&A, 646, A32

4.2 Software Matrix

To facilitate access and long-term usability of the software adopted and developed within EXOHOST, a software matrix has been compiled. The matrix provides a structured overview of each tool, including a short description of its functionality, download links, references to tutorials or documentation, and key publications. This resource is designed to serve as a practical gateway for members of the UTARTU Stellar Physics Group and for the wider community, enabling efficient navigation between tools, supporting materials, and scientific references.

The matrix consolidates all relevant resources in one place, making it easier for early-career researchers to identify suitable codes for specific tasks and helping ensure that the knowledge and tools introduced by EXOHOST remain accessible and exploitable beyond the lifetime of the project.

For readability, this deliverable presents only an excerpt of the matrix: the first ten rows are included in Appendix A. The complete, continuously updated version of the matrix is openly available on the EXOHOST website at https://exohost.ut.ee/software-matrix/.

Conclusions

The EXOHOST project has successfully developed and shared a range of training materials for stellar spectroscopy, addressing both methodological and practical aspects of spectral analysis. The main outcomes can be summarised as follows:

- **Strengthened skills and capacity** within the UTARTU Stellar Physics Group, achieved through workshops, ad-hoc training, and participation in international schools.
- **Modernised software toolkit**, including new and amended codes with accompanying tutorials and documentation.
- **Openly accessible resources**, systematically shared through the project website, Zenodo, GitHub, and related platforms.
- **Wider community benefit**, as the materials are designed for reuse and exploitation beyond EXOHOST.

These outcomes demonstrate that the project has successfully closed the previously identified skills gap and enabled the UTARTU Stellar Physics Group to perform state-of-the-art spectral characterisation of exoplanet host stars and other stellar targets. The group is now better equipped and in a stronger position to contribute to European and global research in stellar astrophysics. The materials and software developed within EXOHOST will continue to support both UTARTU researchers and the broader scientific community, ensuring a sustainable legacy beyond the project's lifetime.

Appendix A: Software Matrix

Excerpt from the Software Matrix: the first ten rows are shown below. The full table is available on the EXOHOST website https://exohost.ut.ee/software-matrix/ .

Software tools developed or amended with EXOHOST support are highlighted in bold.

Software	Public	Description	Links	Publications
Stellar Spectroscopy				
Spectroscopy-Toolbox	☑	The Python-based software can be used for data diagnostics, developing linelists and other tools with the option to add more tools as needed.	https://github.com/Sandipan-Borthakur/spectroscopy-toolbox	Borthakur et al. In preparation
TOFFES-DRP	☑	TOFFES-DRP is the data reduction pipeline based on the PyReduce package. PyReduce is an echelle data reduction algorithm. It is a Python port of the popular IDL data reduction package REDUCE.	https://github.com/Sandipan-Borthakur/TOFFES-DRP https://pyreduce-astro.readthedocs.io/en/latest/index.html	Borthakur et al. In preparation Piskunov & Valenti 2002, A&A 385,1095 Piskunov et al. 2021, A&A, 646, A32
ZMCwrap	☑	ZMCwrap uses a Markov Chain Monte Carlo approach to estimating stellar parameters and chemical abundances, based on an input observation. ZMCwrap is a Python wrapper around the Zeeman spectral synthesis code and uses the emcee package for an MCMC sampler.	https://github.com/folsomcp/ZMCwrap https://github.com/folsomcp/ZMCwrap/blob/main/README.md	Folsom et al. In preparation
Zeeman	☐	Zeeman is a Fortran-based LTE spectral synthesis code. It uses an input 1D model atmosphere and line list, and performs radiative transfer through the atmosphere. Zeeman can model magnetic and non-magnetic stars, with detailed chemical abundances, rotation, and turbulent velocities.	Software is not public	Landstreet 1988, ApJ 326, 967 Wade et al. 2001, A&A 374, 265 Folsom et al. 2012, MNRAS 422, 2072
Zeeman+ (lma)	☐	Zeeman spectral synthesis code extended with a fitting routine, which can be used for estimating stellar parameters and abundances. This uses a chi-squared minimisation routine, adds interpolation between model atmospheres, and is still written in Fortran. This uses an observed spectrum as input, and typically uses a grid of model atmospheres to estimate Teff and logg.	Software is not public	Folsom et al. 2012, MNRAS 422, 2072

Software	Public	Description	Links	Publications
normPlot	☑	A tool for continuum normalising echelle spectra of stars. Can be used as part of SpecpolFlow, or as a stand-alone tool.	https://github.com/folsomcp/normPlot https://folsomcp.github.io/specpolFlow/Tutorials/2-Normalizing_Tutorial.html	Folsom et al. 2025. Zenodo
SpecpolFlow	☑	A set of tools for analysing reduced spectroscopic and spectropolarimetric data. Contains a set of Python functions and classes, and also a command-line interface. Includes tools for coadding spectra, calculating radial velocities, calculating line bisectors, calculating LSD profiles, generating LSD masks, and reading and processing VALD line lists. The version currently in beta adds tools for calculating equivalent widths, plotting VALD line lists.	https://github.com/folsomcp/specpolFlow https://folsomcp.github.io/specpolFlow/	Folsom, Erba, et al., 2025. Journal of Open Source Software, 10(111), 7891 Folsom, Erba, et al., 2025. Zenodo
SUPPNet	☑	Spectrum normalisation neural network (SUPPNet) is a Python-based continuum normalisation code which is used to identify the continuum of an unnormalised stellar spectrum.	https://github.com/RozanskiT/suppnet https://rozanskit.com/suppnet/	Różański, et al., 2022, A&A, 659, A199
iSpec	☑	A versatile tool for the treatment and analysis of stellar spectra. Its main functionalities include cosmic ray removal, continuum normalisation, resolution degradation, radial velocity determination and correction, telluric line identification, and resampling.	https://github.com/marblestation/iSpec https://www.blancocuaresma.com/s/iSpec/manual/usage	Blanco-Cuaresma et al. 2014, A&A 569, A111
MESA	☑	Modules for Experiments in Stellar Astrophysics (MESA) is a widely used stellar evolution code with multiple options for modelling stars and tracking their parameters and compositions. It can simulate processes such as accretion, rotational mixing, and other mixing mechanisms, making it a flexible tool for studying stellar structure and evolution.	https://docs.mesastar.org/en/latest/installation.html https://docs.mesastar.org/en/latest/index.html	https://github.com/MESAHub/mesa/blob/main/CITATIONS.bib
Exoplanets and protoplanetary discs				
Continues at the EXOHOST webpage https://exohost.ut.ee/software-matrix/				