D4.1 Pilot Research Project Reports

EXOHOST

Grant Agreement 101079231

Funded by the European Union

UK Research and Innovation

Document Control Page

Document Control Page	
Document Title:	Pilot Research Project Reports
Project Title:	EXOHOST - Building Excellence in Spectral Characterisation of Exoplanet Hosts and Other Stars
Document Author:	Mihkel Kama
Description:	This document presents the results of the pilot research projects conducted within the EXOHOST Twinning project.
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Date of Delivery:	28.10.2025
Type:	R – Document, report
Language:	EN-GB
Rights:	Copyright EXOHOST
Sensitivity:	☒ Public ☐ Limited ☐ Classified
Status:	☐ In Progress ☐ For Review ☒ For Approval ☐Approved

Document history:

The Document Author is authorised to make the following types of changes to the document without requiring that the document be re-approved:

- Editorial, formatting, and spelling
- Clarification

To request a change to this document, contact the Document Author or Project Coordinator.
Changes to this document are summarised in the following table in chronological order (latest version last).

Revision History			
Version	**Date**	**Created by**	**Short Description of Changes**
0.1	20.10.2025	Mihkel Kama (UCL)	First Draft
0.2	26.10.2025	Anna Aret (UTARTU)	Amendments
0.3	27.10.2025	Anna Aret (UTARTU), Eric Stempels (UU), Luca Fossati (OEAW)	Amendments
1.0	28.10.2025	Merili Jauk (TARTU)	Finalised for submission

Configuration Management: Document Location

The latest version of this controlled document is stored in **EXOHOST Sharepoint Portal**.

Approvers and reviewers			
Name	**Role**	**Action**	**Date**
Eric Stempels	Member of steering board	Reviewed, approved	27.10.2025
Luca Fossati	Member of steering board	Reviewed, approved	27.10.2025
Anna Aret	Project coordinator	Reviewed, approved	28.10.2025

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1 Introduction

1.1 Purpose of the Document

This document presents the results of the pilot research projects conducted within the EXOHOST Twinning project *Building Excellence in Spectral Characterisation of Exoplanet Hosts and Other Stars*. The purpose of the report is to summarise the scientific activities and outcomes that have directly benefited from the training, knowledge transfer, and software development achieved through EXOHOST.

The pilot projects serve as a practical demonstration of how the enhanced skills and modern tools acquired by the UTARTU Stellar Physics Group are now being applied to frontier research topics. They showcase the group's improved capability in spectral analysis, stellar characterisation, and the study of star–planet–disk connections. Each project integrates expertise and methods transferred from partner institutions and represents a tangible step towards the scientific self-sufficiency and international competitiveness envisaged in the Description of Action.

1.2 Project Summary and Objectives

EXOHOST is a Horizon Europe Twinning project aimed at developing excellence in exoplanet and host star research at the Tartu Observatory of the University of Tartu (UTARTU). The project strengthens UTARTU's capabilities in modern stellar spectroscopy, enabling it to become an independent regional leader in the spectral characterisation of exoplanet host stars.

UTARTU's partners in EXOHOST are University College London (UCL), Uppsala University (UU), and the Space Research Institute of the Austrian Academy of Sciences (OEAW) — all internationally recognised for their expertise in stellar and exoplanetary studies.

Exoplanetary systems are the highest-profile topic in Galactic astronomy attracting broad public interest. While discoveries of exoplanets have multiplied rapidly, detailed understanding of their host stars and the connections between stars, disks, and planets remains a key challenge. EXOHOST addresses this gap by combining UTARTU's growing observational capabilities with the advanced modelling and analysis expertise of its partners.

The project's overarching goal is to raise the scientific excellence and competitiveness of the UTARTU Stellar Physics Group through intensive knowledge transfer, collaborative research, and community engagement. Its specific objectives are to:

- Strengthen UTARTU's research capacity in stellar astronomy, particularly in the spectral characterisation of exoplanet hosts and stars with protoplanetary disks.
- Modernise research culture and practices within the UTARTU Stellar Physics Group.
- Enhance UTARTU's international visibility and research profile.
- Improve research management skills and the ability to prepare competitive funding proposals.
- Establish a sustainable foundation for long-term cooperation between project partners.
- Promote gender balance and foster a diverse, inclusive research environment.

The project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101079231 (EXOHOST), and from UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (grant number 10051045).

2 Pilot Research Projects

The pilot research projects were designed to demonstrate in practice how the knowledge, skills, and tools acquired through EXOHOST activities can be applied to frontier research in stellar and exoplanetary science. Their purpose was to translate the enhanced capacity built at the Tartu Observatory of the University of Tartu (UTARTU) into concrete scientific outcomes, while fostering collaboration among project partners and strengthening UTARTU's leadership in the spectral characterisation of exoplanet host stars.

The selection of topics for the pilot projects was guided by the scientific priorities and objectives defined in the EXOHOST Description of Action. Each project focuses on areas where UTARTU researchers, supported by partner expertise, could make immediate progress by applying new methods, tools, and data-analysis pipelines developed during the project. The topics were defined collaboratively through discussions among UTARTU team members and partner institutions, taking into account the group's research interests, available datasets, and the potential for scientific impact and publication.

Collectively, the pilot projects cover complementary aspects of stellar and exoplanet research — from the analysis of stellar spectra and accretion diagnostics to modelling stellar and planetary evolution. Together, they serve as proof of concept that the skills and tools transferred through EXOHOST are now effectively embedded in UTARTU's research practice.

2.1 Implementation and Application of MCMC Techniques in Stellar Spectroscopy

The spectra of stars contain a wealth of information about their physical and chemical properties — including temperature, density, velocity fields, and composition. Through careful modelling, this information can be used to infer fundamental stellar parameters such as mass, radius, and evolutionary stage, as well as to understand processes in stellar and circumstellar environments. Reliable spectroscopic analysis is therefore essential not only for stellar astrophysics itself but also for fields that depend on precise stellar characterisation, such as the study of exoplanets and circumstellar disks.

Within the EXOHOST project, advanced Bayesian techniques were introduced into the UTARTU Stellar Physics Group's research workflow through the development and application of a testbed software solution that couples a Python-based Markov Chain Monte Carlo (MCMC) library with the ZEEMAN stellar spectrum synthesis code (Landstreet 1988; Folsom et al. 2012). This implementation enables the fitting of observed stellar spectra with synthetic models in a statistically robust manner, allowing for the simultaneous determination of multiple interdependent parameters and a more realistic assessment of their uncertainties (***Folsom et al. In prep.***).

During the project, the EXOHOST team fine-tuned, tested, and validated the MCMC-based fitting framework, assessing its stability, performance, and applicability to different classes of stars. To evaluate its practical performance, the team re-analysed GIRAFFE spectra of three stars in the open cluster NGC 5460 (HD 123226, HD 123269, CPD-47 6385). For each target, fundamental stellar parameters — effective temperature (T_{eff}), surface gravity (log g), radial velocity (v_r), projected rotational velocity ($v \sin i$), and microturbulent velocity (v_{mic}) — were derived, together with- abundances for up to twelve chemical elements.

The results obtained using the MCMC-based software were compared with those derived through χ^2 minimisation fits performed with the ZEEMAN code. The comparison demonstrated a high degree of consistency between the two approaches while highlighting several advantages of the MCMC implementation — most notably, the improved estimation of parameter uncertainties and the ability to capture covariances between parameters. These results validate the reliability and robustness of the new method for routine spectroscopic analyses.

The development and testing of the MCMC-based spectral fitting approach were documented in **Deliverable D3.5** – Validated Bayesian Code for Stellar Spectral Fitting. The open-source Python package **ZMCwrap**, with usage instructions and tutorials, is available on GitHub (https://github.com/folsomcp/ZMCwrap). Its successful application to real stellar data within this pilot project confirms the readiness of the method for broader use and establishes it as a standard tool within UTARTU's spectroscopic research.

2.2 Characterisation of Early-Type Stars with Disks and Planets

Accretion from protoplanetary or debris disks, or potentially from evaporating or disintegrating planets, can contaminate the stellar photosphere. This effect is particularly significant in early-type stars with masses above about 1.4 $M_\odot$, which possess radiative envelopes. The mixing of their photospheres with deeper layers is dominated by the relatively slow diffusion or rotational mixing, rather than large-scale convection. As a result, when accreting from disks or planets, these stars can exhibit detectable contamination signatures which manifest as anomalies in their photospheric elemental composition. Accretion onto these stars provides a unique tool for investigating the elemental composition of any circumstellar material.

Within EXOHOST, the UTARTU Stellar Physics Group and project partners applied newly acquired expertise in stellar spectroscopy to several interrelated studies focused on early-type stars. These efforts mark a major step toward establishing UTARTU as a contributor to the international research community investigating star–disk–planet connections.

Characterisation of early-type exoplanet hosts for Ariel

One strand of work focuses on the characterisation of early-type exoplanet-hosting stars in preparation for the Ariel Space Telescope mission (***Ramler et al., in prep.***). This contribution represents the first major peer-reviewed study by newly trained UTARTU experts within the Ariel Stellar Characterisation Working Group. It provides fundamental parameters and chemical abundances for selected targets, ensuring their suitability for exoplanet atmosphere characterisation by Ariel.

Accretion-contamination signatures in early-type stars with gas-rich debris disks

An investigation led by ***Borthakur et al. (2025)*** used a combination of archival data and pre-EXOHOST observations from partner institutions to analyse six A-type stars hosting gas-rich debris disks. Using tools and methods refined through EXOHOST training, the team analysed composition of six gas-rich debris disk-hosting A-type stars to search for links between the stellar surface composition, and their disks or accretion history. A key result, not previously reported in the literature, revealed that the photospheric oxygen abundance in early-type stars decreases with age until the debris disk stage (<20 Myr), after which it appears to rise again. This finding is now being examined in greater detail in a follow-up project *Evolution of oxygen abundances from Herbig to main-sequence A-type stars* (see below).

The phosphorus budget in protoplanetary disks

In this project, the focus is on the first empirical determinations of the refractory fraction of phosphorus in protoplanetary disks. This follows the stellar characterisation methodology of Folsom et al. (2012), and the accretion-contaminated early-type stars method and CAMstars toolkit by Jermyn & Kama (2018), with key expertise and skills contributed by experts across the entire EXOHOST consortium (Amarsi, Borthakur, Folsom, Fossati, Kama, Piskunov, and others). The Hubble Space Telescope (HST) STIS data for all the stars were analysed by Sandipan Borthakur (associated with both UTARTU and OEAW) based on archival HST/STIS spectra using the ZEEMAN code (Landstreet 1988; Folsom et al. 2012), and the phosphorus abundances were measured.

> ***Kama et al. (2025)***. For this paper, experts across EXOHOST brought together different datasets and methods to carry out the most detailed analysis of the phosphorus budget in a planet-forming disk to-date. This included an HST/STIS ultraviolet spectrum and an ALMA spectral dataset on phosphorus-bearing molecules (PO, PN, HCP).
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> ***Borthakur et al. (in prep.)***. Here, the stellar photospheric composition of nine A-type stars with protoplanetary disks was measured using HST/STIS archival data. The main aim was to constrain the fraction of phosphorus locked in dust compared to gas by measuring the degree of correlation with highly refractory elements.

Evolution of oxygen abundances from Herbig to main-sequence A-type stars

Building on the debris-disk study, ***Borthakur et al. (in prep.)*** are conducting a dedicated investigation of the oxygen abundance evolution from Herbig Ae/Be to main-sequence A-type stars. In the gas-rich debris disk hosting star project, the EXOHOST team, led by Borthakur, found that the oxygen abundance in the photospheres of Herbig stars decreases with age until the star loses its protoplanetary disks. Older main-sequence early-type stars show a diversity of oxygen abundance related to the evolution of Herbig stars out of their protoplanetary disk-hosting stage at different times during the oxygen depletion. The oxygen-specific project is focused on a deeper investigation of this previously unknown trend. A large sample of Herbig Ae/Be stars and main-sequence A-type stars has been collected with good age estimates and available high-resolution stellar spectra. A non-LTE abundance correction grid has been developed for oxygen lines of A-type stars to correct the abundances measured under the LTE assumption. A final step of analysis will investigate predicted accreted oxygen abundance trends from a protoplanetary disk evolution model.

Detectability of deuterium in A-type star spectra

In an innovative exploratory project, ***Mitrokhina et al. (in prep.)*** are investigating the detectability of deuterium in the spectra of A-type stars. Because deuterium is normally destroyed in stellar interiors, any detection would imply recent accretion of volatile-rich material, such as gas or dust from a circumstellar disk. Detecting deuterium in such systems would therefore provide direct observational evidence of ongoing or recent accretion processes in early-type stars.

As part of this study, synthetic spectra were generated for effective temperatures between 7 500 and 12 500 K and a surface gravity of log g = 4.0, using the ZEEMAN spectral synthesis code with a grid of ATLAS9 model atmospheres and the VALD atomic line list. Deuterium optical lines were manually inserted into the line list, and MCMC analysis was used to estimate the upper limits of detectability at different signal-to-noise ratios and stellar effective temperatures.

The results establish the theoretical limits under which deuterium signatures could be detected in A-type stellar spectra and provide a benchmark for planning observational campaigns. Current work focuses on applying this method to real observational data to constrain detection thresholds. This project exemplifies the innovative use of EXOHOST-developed data-analysis and modelling skills to explore new diagnostics of accretion in early-type systems.

2.3 Linking exoplanet, disk, and stellar properties

Understanding how stellar properties influence the formation and evolution of planets remains one of the central challenges in exoplanetary science. The chemical composition, age, and rotation of host stars can provide key insights into the physical conditions under which planetary systems form and evolve. Within EXOHOST, the UTARTU Stellar Physics Group has applied the enhanced expertise and analytical capabilities developed through the project to investigate the connections between stellar, disk, and planetary characteristics, thereby addressing one of the core scientific themes of the project.

Planet population synthesis code SPONCHPOP

A new planet population synthesis code, SPONCHPOP[1], has been in development at University College London. Some components of this code have been developed as part of the EXOHOST exploratory science package, to contribute to our efforts of linking the properties of stars to their disks and planetary systems. The code will eventually be released as a stable public version, after development and testing is completed. A reduced version of SPONCHPOP, mainly its planet formation and protoplanetary disk models, have also been used in 2025 and 2024 at a secondary school in east London as part of the Orbyts outreach initiative in the school system in England, teaching Year 10 pupils about favoured conditions of gas giant planet formation. Three papers are currently in preparation, each of which to some degree involves the planet formation module development that has been contributed to SPONCHPOP through EXOHOST.

> ***Kama et al. (in prep)***. A code overview paper introducing the aims and principles of the code along with some examples of potential uses.
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> ***Sommerville-Thomas et al. (in prep)***. Investigating sulfur in planetary cores and atmospheres as a tracer of their formation history. For this project, the planet formation module of SPONCHPOP was combined with a novel gas-grain sulfur chemistry model to produce populations of gas giants over three different protoplanetary disk models with a wide range of input disk parameters, such as viscosity, starting mass, and gas-to-dust ratio.
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> ***Ran et al. (in prep)***. Demonstration of formation and disk parameter retrieval, and associated methodology, for the exoplanet HD 209458 b. This required development of new details in gap opening, migration, and gas accretion physics, and a basic carbon and oxygen chemistry network. The retrieval methodology involved simulation-based inference and neural density estimation. The aim is to combine SPONCHPOP's ability to generate large numbers of simulations with a neural density estimation framework to obtain Bayesian informed constraints on relevant planet formation parameters.

[1] SPONCHPOP: **s**ulfur, **p**hosphorus, **o**xygen, **n**itrogen, **c**arbon, **h**ydrogen, and planet **pop**ulation synthesis

Investigating the dynamical behaviour of circumstellar gas under the influence of gravitational and radiation forces

The interactions between stars and their orbiting planets, driven by forces such as stellar radiation and gravity, play an essential role in shaping exoplanetary atmospheres and gas-rich debris discs. One way to look into the composition of these environments is to observe how they can contaminate the stellar photospheres. For that, we examine how stellar radiation pressure and gravity influence atomic species and analyse their effects across various stellar effective temperatures. Using the radiative-to-gravitational force ratio, we determined the atomic movement direction and assessed the velocity boost imparted to neutral atoms escaping from exoplanet atmospheres or debris discs. Incorporating the solar far ultraviolet/extreme ultraviolet spectrum to address flux discrepancies in the ATLAS9 model, we find that radiation affects atoms differently according to their ionisation state, with highly ionised species less affected by stellar radiation. Our results conclude that the stars most suitable for observing stellar contamination are those between 6,500 and 8,000 K, with neutral noble gases and ionised iron-peak elements as the most likely contaminants.

In this project, the latest atomic data was used in conjunction with stellar radiation field models to re-evaluate the influence of radiation pressure on different ionisation states of a wide range of chemical elements (***Lehtmets et al. submitted***). This is relevant to assess the fate of any tenuous gas in gas-rich debris disks or released by evaporating exoplanets. Expertise available through the EXOHOST consortium was essential to making this project possible.

3 Summary

The pilot research projects implemented within EXOHOST illustrate the successful translation of training and capacity-building efforts into active, high-quality scientific research. Together, they demonstrate that the UTARTU Stellar Physics Group now possesses the methodological expertise, technical resources, and collaborative network required for modern stellar spectroscopy and exoplanet host characterisation.

The projects cover a broad range of interconnected themes — from the development and application of advanced spectral analysis techniques and the study of accretion signatures in early-type stars to modelling the chemical and dynamical evolution of protoplanetary disks and planet populations. These activities have already resulted in **two peer-reviewed publications**, with **one manuscript submitted and eight additional papers in preparation**. This growing body of work highlights the scientific impact of EXOHOST, demonstrating how the enhanced expertise and collaborative framework have translated into sustained research output. Together, these achievements have significantly raised UTARTU's scientific visibility and strengthened its role within the European stellar and exoplanet research community.

Overall, the pilot research projects confirm that EXOHOST has fully achieved its objective of empowering UTARTU to conduct independent, competitive research in the spectral characterisation of stars and their planetary systems. The results clearly show that the group is now in a stronger position to contribute to major international collaborations and to sustain the project's scientific legacy well beyond its lifetime.

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