Time Allocation Committee for
MPG time at the ESO 2.2m-telescope
c/o MPI für Astronomie
Königstuhl 17
D-69117 Heidelberg / Germany

Application No.	
Observing period	April 2023
Received	

APPLICATION FOR OBSERVING TIME

from [X] MPIA [ ] MPG institute [ ] other

1. Telescope: 2.2-m [X] 0110.A-9015(A) **P**

2.1 Applicant

Mr. Alexander J. **Dimoff**	Max Planck Institute für Astronomie
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2.2 Collaborators

Dr. Camilla J. Hansen	MPIA, Göthe Universität Frankfurt
name(s)	institute(s)
Dr. Richard Stancliffe	University of Bristol
name(s)	institute(s)

2.3 Observers

Alexander J. Dimoff	
name	name

By specifying the names under item 2.3 it is obligatory to also send out these observers to La Silla, if required. Correspondence on the rating of this application will be sent to the applicant (P.I.) as quoted under 2.1 above.

3. Observing programme: Category: E

Title : **S-Process Nucleosynthesis in and from AGB Stars**

Abstract : Around half of the heavy elements are formed through the slow neutron capture process (s-process) taking place in e.g., AGB stars ($1 - 6M_\odot$). Different channels can produce s-material either through ^{13}C(α,n) or ^{22}Ne(α,n) reactions. Finer details of the s-process are still not fully understood. However, its nucleosynthetic imprint can be traced directly in the AGB photosphere due to dredged-up material, or indirectly traced in binaries, since systems with AGB stars and less evolved stars through mass transfer will carry the s-process imprint even after the AGB is long gone. Direct or indirect abundance studies of s-process elements (e.g., Rb, Sr, Y, Zr, Tc, Ba, Pb...), will shed light on the physics of s-process nucleosynthesis as well as mass transfer efficiency in binaries.

4. Instrument: [ ] WFI [X] FEROS [ ] GROND

5. Brightness range of objects to be observed: from 6 to 12.5 V-mag

6. Number of hours:

applied for			already awarded	still needed
	30		40	60
no restriction	grey	dark		

7. Optimum date range for the observations: .... 01.04.23 – 30.09.23
Usable range in local sideral time LST: .... 18:30h – 8:00h

Astrophysical context

Observing and computing the photospheric abundances of elements ($Z > 30$) in cool stars rich in s-process material gives insight to the chemical evolution of the Galaxy in the still poorly constrained physics of the s-process. Combined with experimental yields and reaction rates, we will improve on one of the most important open questions in nuclear astrophysics of how heavy elements are formed. Our approach to understanding the s-process is truly interdisciplinary by encompassing observations, theory, and experiments.

Immediate aim

The aim of this proposal is to improve our understanding of s-process nucleosynthesis and stellar evolution through detailed analysis of stellar abundances, binary orbits, and modelling of mass transfer. Towards this end, we require a better census of the elements produced by AGB stars. The goal is to obtain abundances covering the poorly studied s-elements like the light-(Rb) and heavy-(Pb) ones. Stellar abundances and radial velocity measurements will allow us to infer the mass of the star that has produced these elements, because different masses of stars (owing to the different interior properties) are believed to produce different patterns of elements. The mass and internal temperature of the AGB will place important constraints on the s-process reactions.

The recently categorised class of Barium (Ba) stars are perhaps the least well-studied in the metal-rich regime in terms of their elemental patterns (Carbon Enhanced Metal-Poor (CEMP) stars are their metal-poor counterparts). Recent works ([7], [13], [14]) provide a handful of elements, but not enough to constrain the physics of the AGB stars' s-process. A more thorough study of ≥12 elements in a sample of barium-rich binary systems is desperately needed. These elements are observed in the near-UV to blue wavelength region, and FEROS will provide high-resolution spectra allowing for accurate and precise 1D LTE stellar abundances of 12 s-process elements: Rb, Sr, Y, Zr, Nb, Mo, Tc, Ba, Le, Ce, Nd, and Pb. Through catalogues of cool stars, we estimate that currently >300 AGBs or binaries (Ba or CEMP stars) are observable with FEROS.

Previous work

Previous work relating to stellar evolution and s-process nucleosynthesis in AGB stars includes [5], [1], and [15], examining composition and mass transfer of s-process ejecta onto low-mass binary companions. Observations relating to this project include: FEROS P110 (type-B) time and ChETEC-INFRA TNA observing calls at Moletai, Ondrejov, and Rozhen Observatories, where we have observed >200 stars for abundance patterns and radial velocities in the northern hemisphere. However, at the TNA facilities we are magnitude limited to $\sim 10^{th} V_{mag}$. A proposal has been accepted at the Nordic Optical Telescope for P66 & P67 where have already observed 13 stars. For this project, we require a statistically larger sample of Ba and CEMP stars to compare how these groups form s-process elements as a function of metallicity. Many Ba stars and most known CEMP stars are southern targets, highlighting the need for FEROS.

Layout of observations

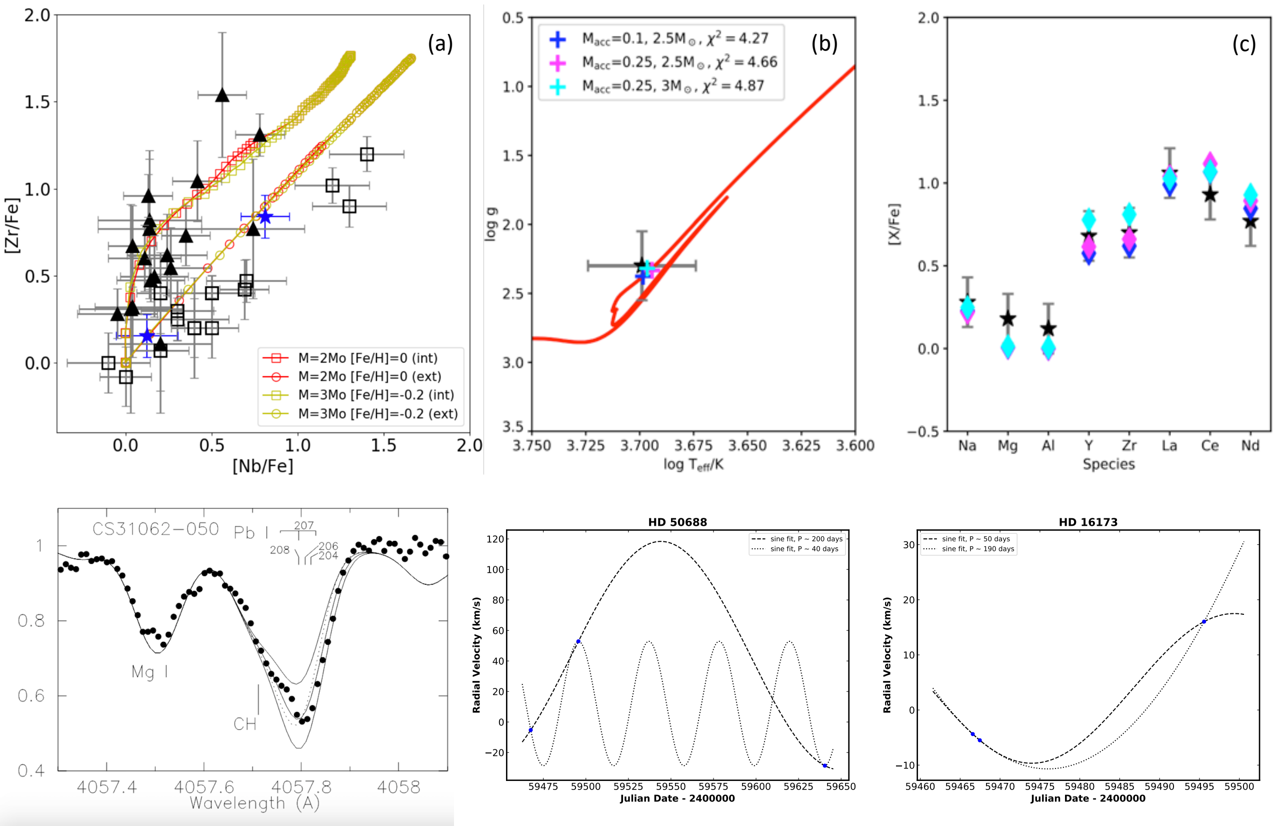
This proposal is part of a long term observation campaign. Here we will target a sample of these stars within the $V_{mag} \sim 10-12.5$ range in the southern hemisphere, visible by FEROS, focusing on abundances and radial velocities from high SNR observations. We form our list of observable stars by selecting from catalogs (e.g., [17], [16], [2], [8], [6], [10]) and the Gaia, GALAH, and LAMOST surveys.

In these observations, we will use FEROS to measure s-process abundance patterns in ∼30 stars. To achieve this, we require SNR of ≥50 at $\lambda \sim$404 nm, where we will observe spectral features of s-process elements including Sr, Ba, Tc, and Pb. The high-resolution of FEROS is required to observe very fine spectral features of these elements (Fig 1 Bottom Left). Pb is very important because only ∼90 stars have Pb abundances measured to date. Statistical uncertainties between previous studies is preventative in tracing the conditions required for mapping the s-process. Our homogeneously analysed observations solves this problem, increases the literature by 50-100%, and will have more complete patterns than current literature data.

Our observations of AGB stars that produce s-process elements will more completely determine their chemical abundance patterns and extend our understanding of their evolution. Additionally, we target binaries (where the AGB has faded away) and the secondary (Ba or CEMP star) has been polluted with s-process materials. Our goal is to investigate mass-loss and -transfer processes in binary systems (Fig 1 Top).

Strategic importance for MPIA

This proposal and project fits within the Galaxies and Cosmology department, within the working groups lead by Dr. Bergemann and Dr. Rix (e.g., 3D and NLTE applying abundance corrections, and binaries). This work will improve our understanding of stellar evolution, s-process nucleosynthesis in low mass stars, mass transfer in binaries, and Galactic chemical evolution. One of the main goals of this project is to compile the largest database of RV measurements and abundances of AGB, CEMP, and Ba stars, beneficial for researching the s-process and cool low-mass stars in binary systems. This database and tailored analysis programs will be publicly available. Uncovering the origin of the elements is one of the open questions in physics, also key to MPIA.



TOP ROW: (a) from Shetye et al. 2020. Zr and Nb abundances in AGB and binary stars comparing to two 2M$_\odot$ and two 3M$_\odot$ AGB models, displaying that accurate abundance measurements within ±0.2 dex are needed to characterise s-process abundance patterns. The ratio of Zr/Nb allow distinction between direct observations of AGB stars or binary systems with mass transfer. (b) and (c) from Stancliffe 2021; Stellar parameters and abundances of Ba stars. Accurate abundances and parameters are needed to constrain the stellar mass and mass loss from the AGB star to the companion. For the majority of Ba stars observed, very few heavy elemental abundances have been computed; in (c) only 5 heavy elements (Z>30) have been observed (Y, Zr, La, Ce, Nd), where we intend to more than double this number.
BOTTOM LEFT: Comparison of the observed (filled) and synthetic (lines) spectra around the Pb I λ4057.8 line for CS 31062-050, from [3]. The observations are made at a spectral resolution of $R \sim$50000 and SNR $\sim$50. This Pb absorption line is blended with a CH feature, and is very close to a Mg I feature. The strong line blends in the blue region highlights the need for high SNR spectra to accurately and precisely identify these heavy element features and measure Pb abundances.
BOTTOM MIDDLE AND RIGHT: Radial velocity curves for a pair of previously observed binaries, HD 50688 and HD 16173. The lack of literature data in these curves emphasises the need for multiple (>10-12) individual RV observations across multiple epochs to constrain orbits for binary systems without an abundance of archival radial velocity data.

Observations are planned at multiple observatories (MPG facilities and ChETEC-INFRA TNA facilities) during each of the upcoming proposal calls over the next ~ 3 years of Mr. Dimoff's PhD studies. Making frequent and reoccurring observations across multiple epochs allows us to form a collection of the largest database of radial velocities and abundances of AGBs / binaries. To reach this goal within the timeframe of the PhD program, multiple observations must be performed each year for the radial velocity monitoring program and to build the database of high-quality abundance pattern measurements. This is achievable by including FEROS in our network of instruments to observe the southern hemisphere.

Other instruments in our network are not able to observe the night sky below the celestial equator or cover fainter stars. As such, FEROS at the MPG 2.2m telescope in La Silla will be of utmost importance observing the southern hemisphere targets, and will be consistently applied to for more time in future proposals. The high-resolution spectrograph, combined with a premier location and consistent weather conditions, provides a unique station to collect extremely high quality data on a consistent basis.
FEROS proposal calls planned for observation:

- P110 (accepted with type-B time in March 23)
- P111 (this proposal, Apr 23 - Sep 23)
- P112 (Oct 23 - Mar 24)
- P113 (Apr 24 - Sep 24)
- P114 (Oct 24 - Mar 25)

High-resolution and high SNR spectra allow computation of abundances and corresponding radial velocity measurements with great precision and accuracy, which provide data for compiling the RV and abundance databases. Reduction and processing of FEROS data will be completed using the CERES pipeline [4], as well as atmospheric parameter estimation and radial velocity computation.

For each of our targets, we will measure and compute a number of parameters. Stellar atmospheric parameters (e.g., T_{eff}, $\log g$, $[Fe/H]$, and ξ) will be estimated from the spectra using the ATHOS and XIRU programs [9], [12]. Stellar orbital parameters (e.g., P, T_0, e, ω, Ω, $a \sin i$) and available physical parameters (e.g., stellar masses) will be computed and optimised using radial velocity profiles and the ELC code [11]. The Bottom Middle and Bottom Left panels of Figure 1 highlight the importance of having multiple accurate radial velocity measurements (>10) over long baselines in time to constrain the binary orbital and physical parameters. We will compute photospheric abundances via stellar spectral synthesis models and equivalent width line measurements using the MOOG/PyMoogi and SMHR programs to characterise abundance patterns.

Nuclear species formation rates, reaction production efficiencies, and interaction cross-sections of the heavy s-process element Pb will be measured experimentally using the Oslo method. Comparing abundance measurements from stellar observations with formation rates from the lab, we will constrain s-process element production rates in stellar interiors. Our resulting data can be used as input for stellar chemical evolution models. Modelling these processes will deepen our understanding of stellar nucleosynthesis and the s-process, as well as Galactic chemical evolution.

9. Objects to be observed

(Objects to be observed with high priority should be marked in last column)

Designation	α (2000)	δ (2000)	magnitude in spectral range to be observed	priority
UCAC2 30705211	$13^h\,04^m\,19^s.46$	$-03°\,29'\,26.80''$	12.08	high
TYC 9244-867-1	$14^h\,06^m\,45^s.30$	$-68°\,46'\,28.32''$	11.69	high
HIP 69788	$14^h\,17^m\,02^s.36$	$+03°\,05'\,09.87''$	10.17	high
HE 1418-0150	$14^h\,21^m\,01^s.17$	$+01°\,37'\,17.83''$	12.01	high
CD-25 10424	$14^h\,35^m\,35^s.81$	$-25°\,57'\,38.34''$	10.19	high
BD-03 3766	$15^h\,21^m\,27^s.14$	$-04°\,14'\,10.95''$	10.60	high
TYC 9260-600-1	$15^h\,47^m\,53^s.46$	$-67°\,41'\,43.06''$	11.25	high
TYC 9277-2435-1	$16^h\,11^m\,45^s.47$	$-70°\,21'\,54.86''$	10.88	high
BD-09 4337	$16^h\,15^m\,29^s.75$	$-09°\,52'\,43.23''$	9.75	high
BD-10 4311	$16^h\,24^m\,13^s.19$	$-11°\,13'\,06.51''$	9.88	high
TYC 8740-23-1	$17^h\,30^m\,43^s.65$	$-59°\,38'\,53.50''$	10.70	high
TYC 8743-1970-1	$18^h\,04^m\,15^s.60$	$-53°\,31'\,21.06''$	10.74	high
TYC 9445-242-1	$18^h\,14^m\,41^s.19$	$-75°\,55'\,30.22''$	11.75	high
V490 Sct	$18^h\,58^m\,27^s.39$	$-13°\,51'\,59.78''$	12.97	high
CD-54 8469A	$19^h\,53^m\,27^s.78$	$-54°\,29'\,32.59''$	10.49	high
CD-54 8469B	$19^h\,53^m\,28^s.08$	$-54°\,29'\,33.26''$	11.56	high
UCAC 14312220	$20^h\,00^m\,02^s.42$	$-41°\,00'\,00.20''$	11.56	high
CD-62 1346	$21^h\,06^m\,02^s.92$	$-61°\,33'\,44.65''$	9.85	high
TYC 5204-375-1	$21^h\,07^m\,19^s.89$	$-07°\,13'\,50.56''$	11.84	high
CD-56 8291	$21^h\,20^m\,32^s.74$	$-56°\,15'\,58.29''$	10.69	high
Gaia DR2 2696956135781037312	$21^h\,50^m\,39^s.01$	$+04°\,55'\,45.96''$	12.02	high
TYC 5215-15-1	$21^h\,53^m\,50^s.06$	$-02°\,30'\,27.01''$	11.27	high
TYC 565-1564-1	$22^h\,10^m\,38^s.77$	$+05°\,16'\,14.60''$	10.73	high
HD 211954	$22^h\,21^m\,17^s.61$	$-27°\,14'\,20.86''$	10.14	high
TYC 7500-902-1	$22^h\,28^m\,47^s.90$	$-34°\,46'\,53.49''$	10.57	high
CD-77 1143	$22^h\,57^m\,43^s.99$	$-77°\,04'\,24.13''$	10.36	high
TYC 591-1090-1	$23^h\,34^m\,56^s.01$	$+07°\,11'\,30.65''$	12.08	high
HE 0017+0055	$00^h\,20^m\,21^s.60$	$+01°\,12'\,06.82''$	11.66	high
HD 5332	$00^h\,53^m\,44^s.59$	$-70°\,29'\,53.41''$	10.00	high
HD 24035	$03^h\,43^m\,42^s.59$	$-72°\,36'\,32.80''$	9.74	high

10. Justification of the amount of observing time requested:

We target heavy elements with weak lines in the blue range of the optical spectrum, and we require high-resolution spectra for accurate and precise abundance determinations. FEROS has good coverage of the blue region of the spectrum, whereas other instruments we have used do not have significant coverage blue-ward of 410 nm and many desired spectral lines are not observed.
Our targets need to be observed with a SNR >50 for photospheric abundance pattern measurements of our ∼12 s-process elements. To achieve this SNR, we use the FEROS exposure time calculator Version P109 with the observing conditions of: airmass = 1.55, seeing = 1.3", fast readout in 1x1 binning, and grey Moon constrains with FLI = 0.5, since our faintest targets are around V_{mag} =12.5.

Representative examples are listed:
V_{mag} = 10.0 T=4500K, 404nm / order 55, SNR ∼50 after ∼1000 s
V_{mag} = 11.0 T=4500K, 404nm / order 55, SNR ∼50 after ∼2200 s
V_{mag} = 12.0 T=4500K, 404nm / order 55, SNR ∼50 after ∼5500 s

The listed exposure times do *not* include overhead. The stars are normal, cool, low-mass stars, and as such we do not require special calibrations; therefore we request day calibrations (bias, flats, wavelength calibrations, etc.). According to the observing manual, this results in around 8 min overhead per exposure. Some fainter targets requiring exposures of more than one hour, resulting in ∼90,000 **sec on targets** + ∼14,400 **sec overhead** for a total of **∼30 hours**.
If backup targets are needed, we have prepared ∼ 50 brighter targets in place that can be used in case of unfavourable weather conditions such as strong winds or light cirrus cloud cover, or time-limited observations. Since our targets spread a wide range in RA, service mode may be better suited to this observing program. However, with the observing experience of our team we are more than capable of completing the observations ourselves (which can be done in ∼5 nights).

11. Constraints for scheduling observations for this application:

12. Observational experience of observer(s) named under 2.3:
(at least one observer must have sufficient experience)

Penn State University, USA, 0.6m telescope. 4 nights of photometric observation and calibration.
San Diego State University, USA, Mt. Laguna 1m telescope. 4 nights of remote photometric observations.
Astronomical Institute, Czechia, Ondrejov 2m Perek Telescope. 1 night visitor spectroscopic observations.
Roque de los Muchachos, Spain, 2.65m Nordic Optical Telescope. 4 nights (upcoming) visitor spectroscopic observations.

13. Observing runs at the ESO 2.2m-telscope (preferably during the last 3 years)
and publications resulting from these

Telescope	instrument	date	hours	success rate	publications

14. References for items 8 and 13:

[1] Abate et al. (2018): *Understanding the Orbital Periods of CEMP-s Stars*, A&A **620**

[2] Alksnis et al. (2001): *General Catalog of Galactic Carbon Stars by C.B. Stephenson. Third Edition*, Baltic Astronomy **10**

[3] Aoki et al. (2002): *A Subaru/High Dispersion Spectrograph Study of Lead (Pb) Abundances in Eight s-Process Element-rich, Metal-poor Stars*, ApJ **580**, 2

[4] Brahm, Rafael and Jordán, Andrés and Espinoza, Néstor (2017): *CERES: A Set of Automated Routines for Echelle Spectra*, PASP **129**, 973

[5] Buntain et al. (2017): *Partial Mixing and the Formation of 13C Pockets in AGB Stars: Effects on the s-process Elements*, MNRAS **471**, 1

[6] Cotar et al. (2019): *The GALAH survey: a catalogue of carbon-enhanced stars and CEMP candidates*, MNRAS **483**, 3

[7] de Castro et al. (2016): *Chemical abundances and kinematics of barium stars*, MNRAS **495**, 4

[8] Escorza et al. (2020): *Binary evolution along the red giant branch with BINSTAR: The barium star perspective*, AAP **639**

[9] Hanke et al. (2019): *ATHOS: A Tool for HOmogenizing Stellar parameters*, Astrophysics Source Code Library, record ascl:1911.006

[10] Karinkuzhi et al. (2021): *Sr and Ba abundances: Comparing machine-learning with star-by-star analyses. High-resolution analysis of suspected LAMOST barium stars*, AAP **654**

[11] Orosz & Hauschildt (2000): *The use of the NextGen model atmospheres for cool giants in a light curve synthesis code*, AAP **364**

[12] Puls et al. (2022): *Chemo-dynamics and asteroseismic ages of seven metal-poor red giants from the Kepler field*, MNRAS **510**, 2

[13] Roriz et al. (2021): *Rubidium in Barium Stars*, MNRAS **501**, 4

[14] Roriz et al. (2021): *Heavy Elements in Barium Stars*, MNRAS **507**, 2

[15] Stancliffe (2021): *The Formation of Barium Giants via Mass Accretion in Binary Systems*, MNRAS **505**, 4

[16] Stephenson (1994): *VizieR Online Data Catalog: General Catalog of S Stars, second edition (Stephenson 1984)*, VizieR Online Data Catalog **1**

[17] Stephenson (1989): *VizieR Online Data Catalog: Cool Galactic Carbon Stars, 2nd Edition (Stephenson 1989)*, VizieR Online Data Catalog

Tolerance limits for planned observations:

maximum seeing:	1.5″	**minimum transparency:**	%	**maximum airmass:**	1.55
photometric conditions:	no	**moon: max. phase / ∠ :**	0.5/30°	**min. / max. lag:**	2/30 nights