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 October 2022 Received

APPLICATION FOR OBSERVING TIME

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

1. Telescope: 2.2-m [X] **P**

2.1 Applicant

Alexander J. **Dimoff**	Max Planck Institute for Astronomy
Name	Institute
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ESO User Portal username	e-mail

2.2 Collaborators

Dr. Camilla J. Hansen	MPIA, Goethe University Frankfurt IAP
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 slow neutron captures in evolved asymptotic giant branch (AGB) stars in the mass range $\sim 1-6M_{\odot}$. At lower temperatures, neutrons are produced through the ^{13}C(α,n) reaction, and at higher temperatures via ^{22}Ne(α,n). The nucleosynthetic imprint of the s-process can be studied by observing dredged-up material in the stellar photosphere; this provides insight into the internal s-process production (of, e.g., Rb, Sr, Y, Zr, Nb, Mo, Tc, Ba, La, Ce, Nd, Pb), and can be studied directly by observing the AGB star, or indirectly by observing companions that have been polluted by a since-faded AGB star. Thus, we need accurate radial velocities and abundances of binary AGB stars to understand the s-process and mass transfer in binaries.

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

5. Brightness range of objects to be observed: from 6 to 13.5 V-mag

6. Number of hours:

applied for			already awarded	still needed
	40		none	none
no restriction	grey	dark		

7. Optimum date range for the observations: .... 1.10.22 – 31.3.23
Usable range in local sideral time LST: .... 17:30h – 5:30h

Astrophysical context

Our approach to understanding the s-process is truly interdisciplinary by encompassing observations, theory, and experiments. 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 by tracing the stellar origins of these elements. Combined with experimental yields and reaction rates, we will improve on one of the most important open questions in physics of how heavy elements are formed.

Immediate aim

The aim of this proposal is to improve our understanding of s-process nucleosynthesis as well as stellar evolution through detailed stellar abundances, binary stellar orbits, and the modelling of mass transfer. To better understand the physics of the s-process, we need a better census of the elements produced by AGB stars. The goal is to obtain abundances covering the light (Rb, Sr…) and heavy (e.g. Pb) s-process elements. Stellar abundances and radial velocity measurements will allow us to infer the mass of the star that produced them, because different masses of stars (owing to their different interior properties) produce different patterns of elements. This and future proposals within this project aim to achieve the same goal.

Barium stars are perhaps the least well studied in terms of their element patterns – recent works ([6], [11], and [12]) provide only a handful of elements, not enough to be able to fix the patterns of elements produced by AGB stars. A thorough census of elements in a range of barium-rich binary systems is desperately needed. These elements are observed in the near-UV to blue wavelength region, and this instrument will provide high resolution spectra allowing for accurate and precise 1D LTE stellar abundances of 12 heavy 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 more than 500 bright AGB stars (potential intrinsic S stars) are observable with FEROS.

Previous work

Previous work relating to stellar evolution and s-process nucleosynthesis in AGB stars includes [13], [4], and [1], examining the composition and mass transfer of s-process ejecta onto low-mass binary companions. Other observations completed relating to this project include ChETEC-INFRA TNA observing calls at Moletai Observatory, Ondrejov Observatory, and Rozhen Observatory, where we have observed a total of 161 stars for abundance patterns and radial velocities. Our proposal has been accepted at the Nordic Optical Telescope for P66 & P67 where we plan to observe >60 stars for s-process abundance patterns.

Layout of observations

This proposal is part of a long term observation campaign. Here we will focus on abundances from high SNR observations, and radial velocities of the selected targets will be measured as well. We will use FEROS to measure s-process chemical abundance patterns in 60 stars. To achieve this, we require SNR $\sim$50 at $\lambda =$400 nm, where we will observe spectral features of s-process elements including Sr, Ba, Eu, and Pb.

Using catalogs from [14], [15], [2], [7], [5], and [9], we compose a sample that totals over 1000 stars (limited to stars brighter than 13.5 magnitude). Here we will target a subsample of these cut at $\sim$13.5 V magnitude in the southern hemisphere, visible by FEROS. We also select targets from Gaia EDR3 observations with more than 10 transits and radial velocity uncertainties >2km/s to increase the chances of selecting binaries.

Our observations target the recently categorised class of Barium (Ba) stars and intrinsic S-stars (AGBs) in the Milky Way to more completely determine and extend our understanding of their chemical abundance patterns and evolution. We will also target extrinsic S-stars (AGB companion dwarfs) to investigate mass loss and material transfer processes in binary systems (see Fig. 1). This will also provide data to further understand the chemical evolution history of the Milky Way galaxy.

Previous observations in this campaign total 161 stars observed for radial velocities, 51 of which for abundances. Following our success being granted time at the Nordic Optical Telescope, Moletai Observatory, Rozhen Observatory, and Ondrejov Observatory, we are moving fainter targets to larger telescopes. Southern targets will be targeted with FEROS to provide a comprehensive demographic across both hemispheres. In total, our goal is to observe our sample of approximately 1000 stars between 6 instruments over the course of this campaign.

Strategic importance for MPIA

This proposal and the corresponding project fits within the Galaxies and Cosmology department, within the working groups lead by Dr. Bergmann and Dr. Rix (e.g. 3D and NLTE applying abundance corrections). 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, S, CEMP-s, and Ba stars, which will be beneficial for researching the s-process, or cool low-mass stars in binary systems. This database and programs tailored to its analysis will be made publicly available.

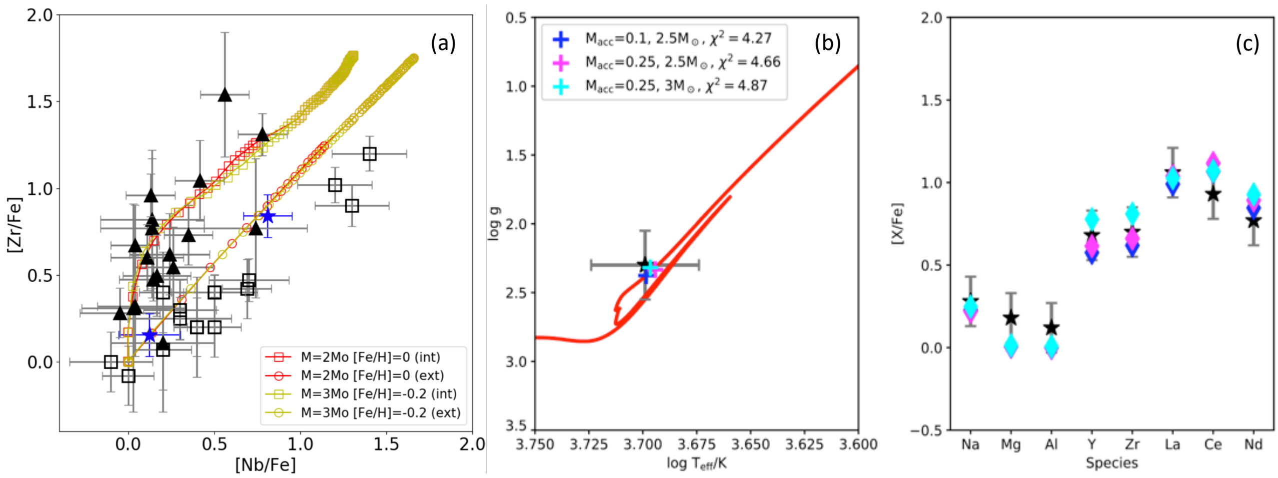

Figure 1: (a) from Shetye et al. 2020. Zr and Nb abundances in AGB and binary stars compared to two $3M_{\odot}$ AGB models, displaying that accurate abundance measurements within ± 0.2 dex are needed to characterise s-process abundance patterns. The ratio of Zr/Nb allow distinction between intrinsic and extrinsic S-stars, which differentiates 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.

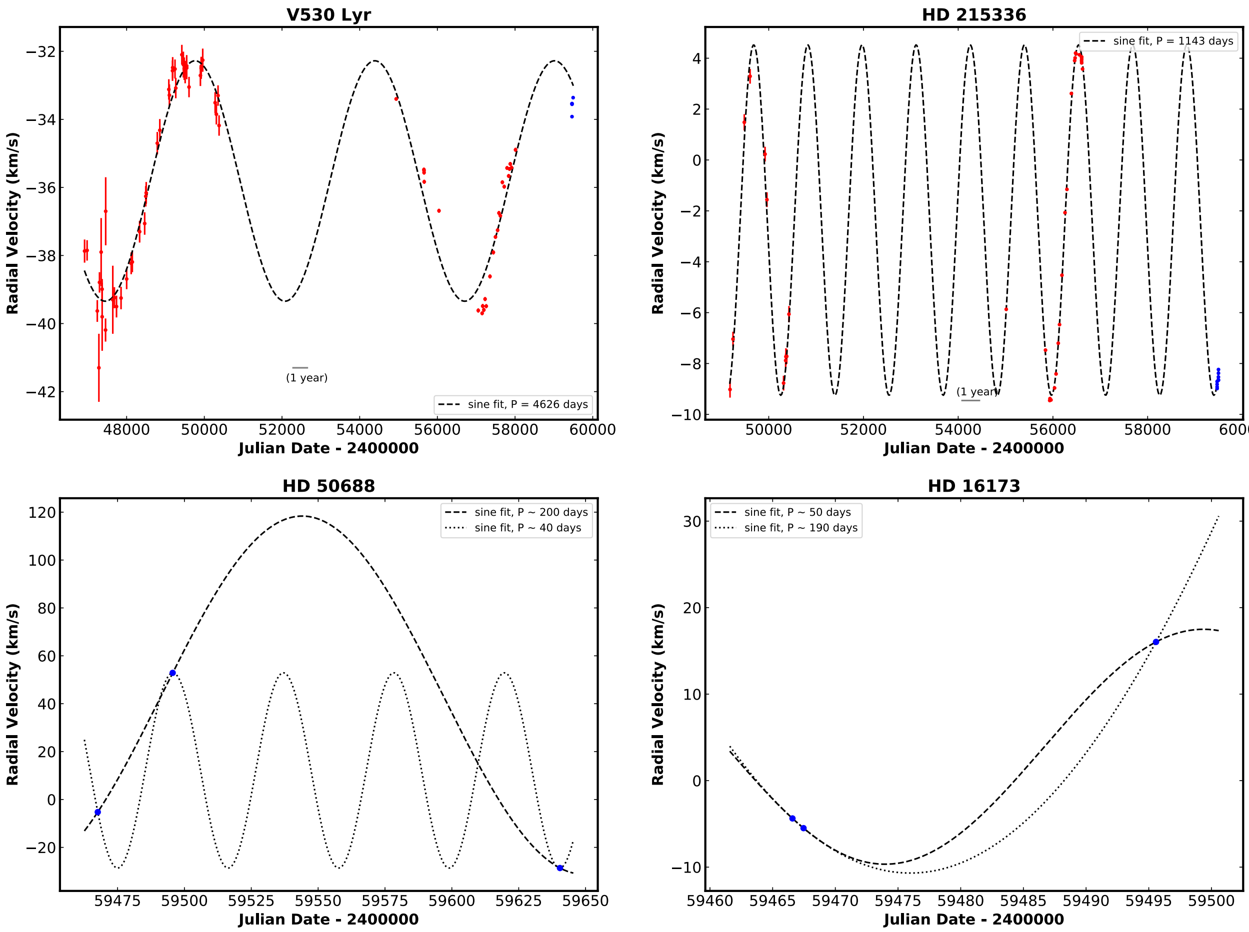

Figure 2: Radial velocity curves for a selection of observed stars. In top panels (V530 Lyr, HD 215336) we add a few data points to a rich set of literature data, allowing both further constraint of the spectroscopic binary orbit and comparison between our measurement uncertainties and those present in the existing data. The bottom panels (HD 50688 and HD 16173) emphasise the need for multiple (12-16) RV observations to constrain orbits for systems without an abundance of archival radial velocity data.

8e. Current logistics of PhD thesis/long term programme

Observations are planned at each observatory (MPG facilities and ChETEC-INFRA TNA facilities) during each of the upcoming proposal calls over the next ~ 3.5 years of Mr. Dimoff's PhD program. Making frequent and reoccurring observations allows us to form a collection of the largest database of radial velocities and abundances of AGB and S-star binaries, ~ 1000 stars. To reach this goal within the approximate 4 years of the PhD program, ~ 250 individual stars must be observed each year, not including followup observations. This is achievable by including FEROS in our network of instruments. As stated above in the Layout of Observations, we collect targets from the listed set of catalogs and Gaia DR3.

Other instruments in our network are not able to observe the night sky below the celestial equator. 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.

Upcoming FEROS proposal calls planned for observation:

- P110 (this proposal, Oct 22 - Mar 23)
- P111 (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 will provide data fit for compiling the RV and abundance database. Reduction and processing of FEROS data will be completed using the CERES pipeline [3], as well as atmospheric parameter estimation and radial velocity computation.

Stellar atmospheric parameters will be estimated from the spectra using the ATHOS program [8]. Stellar orbital parameters (P, e, ω, $a \sin i$) and physical parameters (e.g. stellar masses) will be computed and optimized using the radial velocity profiles and the ELC code [10]. Figure 2 displays the importance of multiple radial velocity measurements (12-16) over long baselines in time to constrain the binary orbital and physical parameters. Abundances will be computed via stellar spectral synthesis models using the MOOG/PyMoogi programs.

Formation rates, production efficiencies, and interaction cross-sections of the heavy s-process element lead (Pb) will be measured experimentally using the Oslo method. With abundance measurements from stellar observations and formation rates from the lab, we will constrain s-process element production rates in stellar systems, and use our observational data as inputs 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
HR CMa	$06^h\,32^m\,46\overset{s}{.}8731$	$-11°\,09'\,58.9874''$	6.24	high
HD 269246	$05^h\,14^m\,47\overset{s}{.}7734$	$-69°\,11'\,28.1564''$	8.83	high
2MASS J03145506-6656591	$03^h\,14^m\,55\overset{s}{.}0518$	$-66°\,56'\,59.2030''$	10.93	high
HD 84759	$09^h\,45^m\,12\overset{s}{.}7459$	$-59°\,28'\,33.1764''$	7.64	high
HD 224959	$00^h\,02^m\,08\overset{s}{.}0215$	$-02°\,49'\,12.2327''$	9.55	high
GaiaDR2 2550369657883109504	$00^h\,43^m\,59\overset{s}{.}1207$	$+02°\,34'\,07.8676''$	13.3	high
HE 0017+0055	$00^h\,20^m\,21\overset{s}{.}6000$	$+01°\,12'\,60.8176''$	11.66	high
HE 0414-0343	$04^h\,17^m\,16\overset{s}{.}4631$	$-03°\,36'\,31.3887''$	11.04	high
TYC 4790-5460-1	$06^h\,02^m\,03\overset{s}{.}3119$	$-05°\,03'\,46.8881''$	11.87	high
UCAC2 30705211	$13^h\,04^m\,19\overset{s}{.}4635$	$-03°\,29'\,26.7986''$	12.08	high
Gaia DR2 3854012834900183936	$09^h\,39^m\,38\overset{s}{.}8711$	$+06°\,31'\,49.5552''$	12.02	high
Gaia DR2 579592852909815552	$09^h\,15^m\,43\overset{s}{.}4832$	$+04°\,32'\,30.6564''$	12.70	high
Gaia DR2 3337834353779474432	$05^h\,30^m\,46\overset{s}{.}4529$	$+09°\,12'\,29.3719''$	13.06	high
TYC 54-642-1	$02^h\,53^m\,04\overset{s}{.}3953$	$+06°\,20'\,47.5973''$	11.28	high
TYC 701-80-1	$05^h\,31^m\,45\overset{s}{.}5513$	$+09°\,06'\,46.6252''$	11.31	high
TYC 126-853-1	$05^h\,33^m\,07\overset{s}{.}3483$	$+05°\,54'\,56.4477''$	11.51	high
HD 211173	$22^h\,15^m\,57\overset{s}{.}0093$	$-31°\,51'\,38.5294''$	8.49	high
HD 211221	$22^h\,16^m\,14\overset{s}{.}6772$	$-31°\,23'\,30.6385''$	9.41	high
HD 214579	$22^h\,39^m\,32\overset{s}{.}0780$	$-22°\,46'\,44.0428''$	8.24	high
HD 214889	$22^h\,41^m\,23\overset{s}{.}6384$	$-07°\,53'\,12.2179''$	8.91	high
HD 749	$00^h\,11^m\,38\overset{s}{.}0955$	$-49°\,39'\,21.7406''$	7.88	high
HD 5332	$00^h\,53^m\,44\overset{s}{.}5876$	$-70°\,29'\,53.4116''$	10.00	high
HD 18182	$02^h\,55^m\,11\overset{s}{.}0938$	$-04°\,18'\,59.8716''$	8.97	high
HD 21989	$03^h\,28^m\,58\overset{s}{.}5989$	$-63°\,57'\,42.2826''$	8.16	high
HD 22772	$03^h\,35^m\,14\overset{s}{.}9585$	$-67°\,51'\,46.1770''$	9.31	high
HD 26886	$04^h\,14^m\,58\overset{s}{.}8385$	$-00°\,59'\,50.8029''$	7.99	high
BD-18 821	$04^h\,22^m\,30\overset{s}{.}8318$	$-17°\,57'\,42.6057''$	9.43	high
HD 29370	$04^h\,35^m\,40\overset{s}{.}0434$	$-42°\,00'\,05.5955''$	9.33	high
HD 32712	$05^h\,01^m\,34\overset{s}{.}9151$	$-58°\,31'\,15.0464''$	8.55	high
HD 69578	$08^h\,12^m\,43\overset{s}{.}6193$	$-68°\,21'\,27.8956''$	9.70	high
HD 87080	$10^h\,02^m\,00\overset{s}{.}8592$	$-33°\,41'\,06.5048''$	9.37	high
HD 92545	$10^h\,40^m\,57\overset{s}{.}7070$	$-12°\,11'\,44.2255''$	9.15	high
(list truncated)				

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, where as other instruments we have used do not have significant coverage blueward 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 ETC with the observing conditions of: airmass = 1.55, seeing = 1.3, fast readout and 1x1 binning, and grey Moon constrains with FLI = 0.5, since our faintest targets are around V = 13.5 mag.
Representative examples are listed below:
Vmag = 9.0 T=4500K, 404nm / order 55, SNR ~50 after 400 s
Vmag = 10.0 T=4500K, 404nm / order 55, SNR ~50 after 800 s
Vmag = 11.0 T=4500K, 404nm / order 55, SNR ~50 after ~2000 s
Vmag = 12.0 T=4500K, 404nm / order 55, SNR ~50 after ~5000 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.). From the observing manual, this results in about 8 min overhead per exposure. Some fainter targets requiring exposures of more than one hour, resulting in ~110,000 **sec on targets** + ~28800 **sec overhead** for a total of ~**40 hours**.
If backup targets are needed, we have ~ 50 brighter targets in place that can be used as fillers in case of unfavourable weather conditions such as strong winds. 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 capable of completing the observations ourselves (which can be done in ~4 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 0.6m telescope. 4 nights of photometric observation and calibration.
San Diego State University Mt. Laguna 1m telescope. 4 nights of remote photometric 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] Brahm, Rafael and Jordán, Andrés and Espinoza, Néstor (2017): *CERES: A Set of Automated Routines for Echelle Spectra*, PASP **129**, 973

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

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

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

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

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

[9] 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**

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

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

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

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

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

[15] 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:	**moon: max. phase / ∠ :** °	**min. / max. lag:** nights