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 - September 2022
Received

APPLICATION FOR OBSERVING TIME

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

2.1 Applicant

Eleonora **Zari**	MPIA
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ESO User Portal username	e-mail

2.2 Collaborators

K. El-Badry, L. Seeburger	MPIA; MPIA
name(s)	institute(s)
H.-W. Rix,	MPIA
name(s)	institute(s)

2.3 Observers

service	
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: D

Title : **Surveying the Brightest Luminous and Hot Stars in the Milky Way**

Abstract : We propose FEROS multi-epoch spectroscopy of 505 Galactic OB stars. This program will serve as a crucial complement to a major aspect of the SDSS-V all-sky survey: observing $\sim$ 500.000 massive hot stars throughout the Galactic disk with multi-epoch $\mathcal{R} \sim 2,000$ spectrosopy. SDSS-V aims to map young massive stars in the Milky Way, to study the interaction between stars and the ISM, and to characterise their multiplicity properties, including dormant black hole (BH) companions. The proposed observations complement SDSS-V by obtaining spectra of the $\sim$ 505 Southern O(B) stars too bright for the survey and by verifying candidates for dormant BH + OBA binaries via multi-epoch spectral disentangling that eliminates false positives. The proposal is the Southern complement to our STAC-approved analogous effort with FIES at NOT.

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

5. Brightness range of objects to be observed: from 4 to 8 *Gaia* G mag

6. Number of hours:

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

7. Optimum date range for the observations: .... 01.10.2022 – 03.31.2023
Usable range in local sideral time LST: .... 0:00h – 24:00h

Astrophysical context

Massive stars dominate the interaction between stars and interstellar gas; they trace of massive star formation and probe spiral structure across our Galaxy; they are the only channel to yield binaries that involve stellar-mass black holes and neutron stars in the disc of the Milky Way. Mapping and understanding massive stars – here, Galactic OBA stars – is a crucial aspect of the SDSS-V survey, which can offer order-of-magnitude progress but needs to be complemented with FEROS data.

SDSS-V has just started (Feb 2022) as the first survey ever to cover most of the sky with multi-epoch optical and near-IR spectroscopy [6]. For hot, OBA stars it delivers multi-epoch (3 or more), R$\sim$2,000 spectroscopy across the entire optical range (BOSS), with a focus on low Galactic latitudes. The sample of OBA stars [10] was designed for three main purposes: **(1)** To map the Milky Way disk in young stars, delineating Galactic star formation over the last 100 Myr. **(2)** To provide input on the stars that heat or ionize the local ISM, to mesh with SDSS-V's Local Volume Mapper project, which aims to make a 3D spectroscopic map of the Hα-bright sky [6]. **(3)** To provide a comprehensive, spectroscopic, multi-epoch census across the Galaxy of massive stars, their evolutionary phases and binarity, including black hole companions.

SDSS-V's OBA star sample ([10] & Figure 1, left) encompasses stars that are luminous ($M_K < 0$), hot (> 7000 K) and G<16 mag and consists of about 500,000 targets (at distances $d < 4$ kpc) that should get ≥ 3 spectroscopic epochs during SDSS-V. In [9] we have shown that from R$\sim$2,000 spectra we can get basic stellar parameters, log$g$, T_{eff}, v sin(i) and ages. We can also diagnose velocity variations ≥ 15 km/s to give us statistical multiplicity information and candidates of massive stars in orbit around massive dark companions. This latter aspect is central to the just-approved ERC Advanced Grant *Hunting Dormant Stellar Black Holes* (PI: H.-W. Rix).

Immediate aims

1) SDSS-V spectroscopy will be limited to $G > 8$, not to saturate the detectors, which is problematic for the science of SDSS-V's LVM program. In brief, LVM aims to construct a detailed IFU of the Hα-bright part of the Galactic disk to map the kinematics, the densities and temperatures of the ionized ISM, along with the ionizing conditions and abundances. As a complement, we need a map (and the physical parameters) of the star most important for ISM-feedback in this region: O and early B stars. Yet, many of them within 1-2 kpc are brighter than $G = 8$ mag. Therefore, we need systematic and consistent spectroscopy for all star $G < 8$mag with presumed masses higher than $8M_\odot$ and temperatures $\geq 12,000$ K. For these stars we also need some assessment of their (close) binarity, as it affects (e.g. via mass transfer) their lifetimes and UV photon rates.

2) SDSS-V spectra can provide candidates for the exciting case of (massive) stars orbiting a dormant neutron star or black hole (in conjunction with TESS and Gaia data). Yet, recent experience has shown (e.g. [1]) that short-lived binary star phases are a dominant source of "false positives". So far, the candidate systems have turned out to be bare stellar cores of subsolar mass that formed through previous mass-transfer and now briefly (10^{5-6} years) masquerade as a hot, luminous and massive stars. Elimination of such false positives requires *spectral disentangling*, to reveal a second luminous component if it exists, or prove the companion is "dark". The upcoming Gaia DR3 data release will provide many candidates, which will also be subject to the risk of such false positives.

Previous work

The science cases outlined above are critically enhanced by multi-epoch, high-resolution follow-up spectroscopy. As SDSS-V is all-sky, this follow-up must come from both hemispheres. We have already obtained time in the Northern hemisphere at NOT with FIES, and we plan to use the 2.2m with FEROS on la Silla to complete the follow up in the Southern hemisphere. In parallel to the observational effort, pipelines are being developed developed to homogeneously analyse whole samples of spectroscopic data [9, 5, 8] and to perform spectral disentangling [2]. We also have developed a well-working pipeline for FEROS reduction/analysis of hot stars.

Layout of observations

For each target we require three epochs (one epoch separated by at least one month, one epoch separated by one year – the proposal thus should extend over three semesters) to detect RV differences and probe for binarity. We request single spectra with S/N ≥ 50 at 4000Å for measuring RVs, $T_{\rm eff}, \log g, vsini$, [Fe/H], and chemical abundances with sufficient precision. Further we request 10 epochs for the 20 most promising SDSS-V and Gaia DR3 Southern candidates of hot massive stars with possible dark massive companion.

Strategic importance for MPIA

MPIA has leading involvement in the SDSS-V survey, and this program is central to H.W.Rix's just-approved ERC Advanced grant which will fund operations for a total of 180 nights of MPIA 2.2m time with FEROS. We would like to front-load this part of the ERC program (Hunting Dormant black holes) as much as possible; hence the large request. The requested data is also part of the PhD project of one of the co-I's (L. Seeburger).

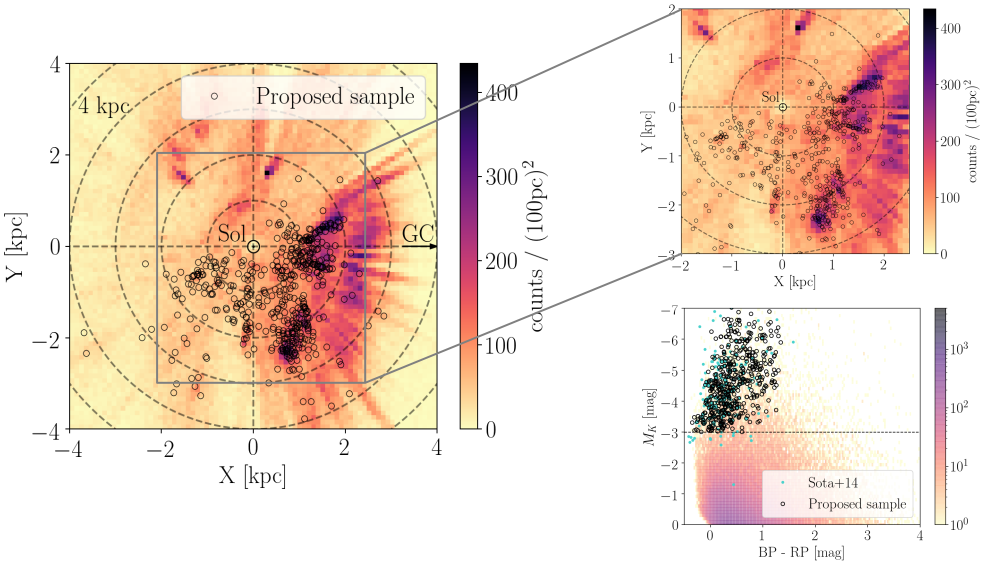

Figure 1: **Left**: distribution of the young OBA star in the galactic plane as identied by Zari, Rix, et al (2021). The sun is located at (X,Y) = (0 kpc, 0 kpc) and the galactic center at (8.2 kpc, 0 kpc). The black empty circles show the proposed sample distribution. **Top right**: Zoom-in of the OBA star map shown on the left. **Bottom right**: Colour-magnitude diagram of the sources in Zari, Rix, et al. (2021). The cyan dots show the sample of spectroscopically confirmed O-type stars from Sota et al. (2014). The black empty circles show our proposed sample.

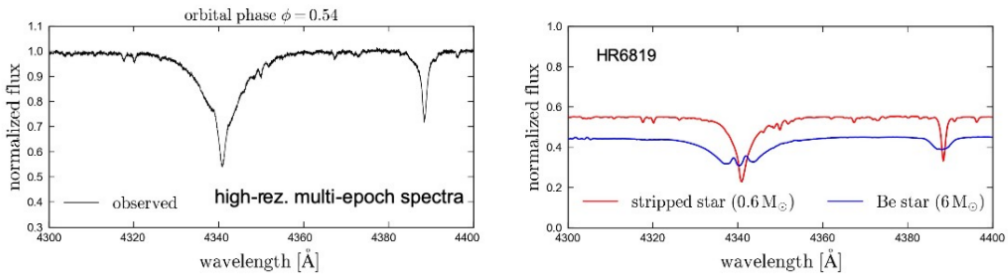

Figure 2: Illustration of spectral disentangling for a B star + dormant BH binary candidate, HR 6819. The left panel shows one (of ∼ 10) epoch observation of the system; the right panel the two components separated by disentangling. This candidate star-BH binary candidate turned out to be a star-star binary, with a luminous, hot but low-mass component (red line) and a luminous but rapidly-rotating companion (blue line). Detection of such rapidly-rotating companions requires high-resolution, many-epoch spectroscopy, as proposed here.

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
HD 46484	$06^h\,33^m\,54.41^s$	$+04^\circ\,39'\,44.61''$	7.6405606	1
ksi01 CMa	$06^h\,31^m\,51.36^s$	$-23^\circ\,25'\,06.32''$	4.2663584	1
HD 43910	$06^h\,19^m\,21.98^s$	$+12^\circ\,59'\,24.17''$	7.214111	1
HD 159110	$17^h\,34^m\,40.46^s$	$-41^\circ\,19'\,27.13''$	7.5413766	1
HD 158799	$17^h\,33^m\,07.39^s$	$-41^\circ\,10'\,23.04''$	5.7985325	1
V* V961 Cen	$13^h\,16^m\,04.80^s$	$-62^\circ\,35'\,01.49''$	7.868011	1
HD 56597	$07^h\,17^m\,07.35^s$	$-13^\circ\,59'\,23.32''$	7.7723117	1
HD 164896	$18^h\,06^m\,09.21^s$	$-51^\circ\,44'\,38.06''$	6.4055767	1
HD 104705	$12^h\,03^m\,23.90^s$	$-62^\circ\,41'\,45.83''$	7.7720923	1
HD 106146	$12^h\,13^m\,01.56^s$	$-62^\circ\,18'\,46.57''$	7.6906805	1
[a]				

[a]Only the first 10 entries of the 505 candidates OB stars are shown. The full sample is listed in the accompanying ASCII file and at this link: https://keeper.mpdl.mpg.de/f/91c01b22aa4f487fb356/?dl=1.

10. Justification of the amount of observing time requested:

The science goals above translate into the following set of proposed observations.
1) We will take 3-epoch spectra of **all** Southern ($\delta > -70°$ & $\delta < 20°$) bright stars that are very luminous and blue, specifically satisfying $G_{Gaia} < 8.$ and $M_K < -3$. The latter cut is empirically derived from the distribution in the colour-magnitude diagram of the spectroscopically confirmed O-type stars from [7] (see Fig. 1). All the proposed targets are included in the overall SDSS-V OBA stars sample [10], and are distributed in the Galactic disk as shown in Figure 1. From isochrones we expect those stars to be mostly $M > 8\ M_{\odot}$ with temperatures $T_{eff} > 12.000$ K, i.e. the stars most important for ISM feedback. The parent sample with these cuts contains 505 stars; we aim to get spectra for $\geq 85\%$ of them. We require $S/N \geq 50$ at 4000Å for measuring RVs at the various epochs ($\sim$ 1 km/s precision suffices), as well as atmospheric parameters, rotation rate, and select chemical abundances ($T_{\rm eff}$, $\log g$, $v \sin i$ [Fe/H], [X/Fe]) with sufficient precision. For the faintest objects in the O(B) star sample ($G \sim 8$) this can be reached in $\leq$250 sec (following the FEROS exposure time calculator). The total overhead per target is $\sim$ 570 sec, including 1) 360 sec for the telescope pointing, target acquisition and centring on fibre; 2) 60 sec for the FCU + Adapter setup; 3) 150 sec for slow, high-gain read-out (FEROS User Manual, Issue 78.0, Date 15/10/2006). We presume that shorter exposure times will not yield significantly faster execution of the overall program, because of inter-target overheads. This results in $\sim$ 345 hours of observing time including 3 epochs for all OB targets and overheads. Of these, $> 50\%$ ($\sim$ 230 hours, i.e. 2 epochs) of the data should be obtained in the upcoming semester.
2) We propose to obtain 10 epochs for 20 of the most promising SDSS-V and Gaia DR3 Southern candidates of hot massive stars with possible dark massive companions (either massive WDs, neutron stars or BHs); these will be systems that have orbital periods of a few months to years. The goal here is to verify that the companion is dark, by attempting to detect a second luminous component via spectral disentangling (Figure 2). Their coordinates will only be known after Gaia DR3 (June 13, 2022). We thus require $\sim$ 45 hours of observing time including 10 epochs for all dark companion candidates and overheads. The actual candidates will only be available after Gaia DR3 (June 13, 2022).
In summary, we require 3-epoch observations for 505 OB stars candidates and 10-epoch observations for 20 of the most promising dormant black hole binaries from SDSS-V and Gaia DR3. This makes for a total of 1715 spectra (=targets$\times$epochs), and $\sim$390 hours or 40 nights without any weather losses. Assuming a weather-compensation factor of 1.2, this leads to the request of 48 nights, of which $\sim$ 30 should be obtained in the upcoming semester and the remaining $\sim$ 18 in subsequent semesters.

11. Constraints for scheduling observations for this application:

For the candidate dormant BH binaries the details of the period-spacing are not critical, as long as they are distributed across at least a period.
The 3-epoch observations for the nearby O(B) stars should be ideally spaced across at least one lunation period, with one of the three periods in a separate year: hence the long-term proposal. This is to diagnose binarity in these systems with periods $\geq$ 1 year. This calls for queue observations rather than visitor mode.

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

We anticipate service observing under the current agreement, possibly with added funds from the GC department for service observing.

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

Telescope	instrument	date	hours	success rate	publications
2.2m	FEROS	Dec 20	60	80%	[4] + in prep
2.2m	FEROS	Aug 21	100	50%	[3] + in prep

14. References for items 8 and 13:

[1] El-Badry, & Quataert, 2021, MNRAS, 502, 3436

[2] El-Badry, K., Seeburger, L., et al., 2022, MNRAS, 512, 5620

[3] El-Badry, K., et al. 2022, MNRAS, 512, 5620

[4] El-Badry, K., et al. 2022, Arxiv: 2201.05614, MNRAS, submitted

[5] Gebruers, S., Straumit, I., Tkachenko, A., et al. 2021, A&A, 650, 151

[6] Kollmeier, Zasowski, Rix H.-W. et al., 2017, ArXiv:1711.03234

[7] Sota, Maiz Apellaniz et al., 2014, ApJS, 211, 10

[8] Straumit, I., Tkachenko, A., Gebruers S., et al. 2022, AJ, 163, 236

[9] Xiang, Rix, Ting, et al., 2021, ArXiv:210802878

[10] Zari, Rix, Frankel et al., 2021 A&A, 650, 112

Tolerance limits for planned observations:

maximum seeing:	4″	**minimum transparency:**	50%	**maximum airmass:**	2
photometric conditions:	no	**moon: max. phase / ∠ :**	1/20°	**min. / max. lag:**	1/60 nights