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

| | |
|---|---|
| Kareem **El-Badry** | MPIA |
| Name | Institute |
| Königstuhl 17 | D-69117 Heidelberg |
| street | ZIP code - city |
| kelbadry | kelbadry@mpia.de |
| ESO User Portal username | e-mail |

2.2 Collaborators

| | |
|---|---|
| L. Seeburger; S. Almada; M. Xiang; | MPIA; MPIA; MPIA |
| name(s) | institute(s) |
| E. Quataert; D. Weisz | Princeton; Berkeley |
| 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: E

Title : **A search for detached black holes and neutron stars in binaries**


Abstract : We propose FEROS spectroscopy to measure multi-epoch radial velocities (RVs) for a sample of ~150 bright (*Gaia* $G = 7 - 13.5\,\mathrm{mag}$), nearby ($d < 2\,\mathrm{kpc}$) stars that are candidates for having non-accreting black hole and neutron star companions with periods of days to months. Our sample combines targets selected via TESS light curves (short periods) and *Gaia* DR3 astrometric orbits (long periods). We will obtain 3 RVs for each target with typical precision of $1\,\mathrm{km\,s^{-1}}$. Our observations, complemented by previously obtained photometric constraints on the binaries' orbital periods, will provide absolute lower limits on the mass of the stars' unseen companions. These observations will shine light on the Galactic population of non-accreting compact objects and test theoretical models of binary evolution.


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

5. Brightness range of objects to be observed: from 7 to 13.5 *Gaia* G mag

6. Number of hours:

| applied for | | | already awarded | still needed |
|---|---|---|---|---|
| 140 | | | none | none |
| no restriction | grey | dark | | |

7. Optimum date range for the observations: ........................... 06.01.2022 – 09.31.2022
Usable range in local sideral time LST: ..................................... 0:00h – 24:00h

## Astrophysical context

The Milky Way is thought to contain between $10^5$ and $10^8$ stellar mass black holes (BHs) [1, 2, 3]. However, only ∼20 BHs are dynamically confirmed. Almost all of these are accreting from a companion and were discovered via X-rays. Recent work has produced a few candidate BHs in binaries that are not accreting [4, 5, 6, 7, 8], but their status as BHs is not unambiguous. The non-accreting BH population – which in fact must contain the vast majority of the stellar-mass BHs – remains largely unexplored.

Basic open questions include the magnitude of natal kicks for BHs, the fraction of BHs formed by direct collapse rather than supernovae, the initial-final mass relation for massive stars, and the evolutionary pathways through which X-ray binaries form. The BH population will be mapped in detail in the next decade by searches using gravitational waves (LIGO), astrometric orbit modeling (*Gaia* DR3), microlensing (Roman/WFIRST), and multi-epoch RVs (SDSS-V), but these waters are thus far still uncharted.

Theoretical predictions for BH and neutron star (NS) binary population statistics disagree considerably between models. For example, varying the fraction of a binary's orbital energy that is coupled to the envelope of the BH progenitor during common envelope evolution (the "$\alpha$" parameter) changes the number of predicted close BH-main sequence (MS) binaries by orders of magnitude [9, 25]. The discovery of *any* detached BH companions to low-mass stars ($M < 3\,M_\odot$) would rule out some models, which predict that binaries cannot survive when the mass ratio is large. The population of detached neutron stars in binaries is also uncertain and deserving of study: these are the progenitors of most X-ray binaries, binary pulsars, and kilonovae.

*Even if our search returns no BHs, the resulting lower limits will yield strong constraints on evolutionary models.* Recently, [10, 25] carried out population synthesis simulations to determine specifically how many detached BH-MS binaries should be discoverable via our search strategy. They predicted that more than 100 such binaries should already have light curves from TESS. If none of our candidates end up having credible BH companions, our search will rule out a wide range of binary evolution models.

## Immediate aim

We propose to obtain multi-epoch RVs for ∼150 bright main-sequence stars selected based on light curve variability (targets already in hand) and astrometric orbits (targets expected from *Gaia* DR3). At orbital periods of less than a week, the combination of ellipsoidal modulation due to the tidal field of a companion and relativistic Doppler beaming produce light curves with an easily-identifiable shape (e.g. Figure 1). At longer periods (weeks to months), the photocenter of a binary traces a measurable ellipse on the sky, detectable for the first time with *Gaia* DR3.

Several contaminants exist. Our pilot studies in P107-108 showed that the most common contaminants are (a) rotating stars with spots, which can produce almost any light curve shape and sometimes happen to mimic the shape we select on, and (b) low-amplitude gravity-mode pulsators. RVs are thus crucial for distinguishing true NS/BH+MS binaries from contaminants.

We propose to obtain 3 epochs of RVs, spread over 3 different nights, for each of these targets. This will be sufficient to eliminate most contaminants: in binaries containing a BH or NS, there will be large RV shifts from one night to the next, and light curve models (or astrometric fits) predict precisely what they should be. Pulsators and spotted-star contaminants will not usually have night-to-night RV shifts; when they do, they will be smaller than predicted for a BH/NS companion.

## Previous work

Earlier versions of this proposal were approved for P105 and 107, but were in both cases canceled to due to COVID-19. We did obtain data for ∼75 targets in P106 and P108, demonstrating the efficacy of our approach at short periods (Figure 2). These observations will be the first in our program to follow-up wider binaries selected from *Gaia* astrometric orbits. The proposers have done extensive work in the most relevant areas: reducing and modeling of stellar spectra to derive velocities and atmospheric parameters [15, 16], and population modeling and statistical inference [17, 18].

## Layout of observations

Our targets are distributed across the southern sky; on any given night in P109, about 70% are observable from La Silla at some point in the night. To maximize the number of targets we can observe and to make use of *Gaia* DR3 (expected in spring 2022), we request that our observations are spread out somewhat (e.g., a week in June/July and a week in August/September). It is not critical that nights be consecutive. In most cases, 3 epochs of RVs and a light curve (or astrometric ellipse) will sufficient to fully constrain the orbit. We will obtain additional RVs for the most promising targets (i.e., those with the largest RV shifts and implied companion masses).

## Strategic importance for MPIA

MPIA has invested in several upcoming spectroscopic surveys that aim to discover stellar remnants in binaries (SDSS-V, 4MOST, WEAVE, *Gaia*). This pilot program will pave the way for larger-scale searches in the coming years. Analysis of this data set will be an important component of the master's thesis of CO-I S. Almada and PhD thesis of CO-I L. Seeburger

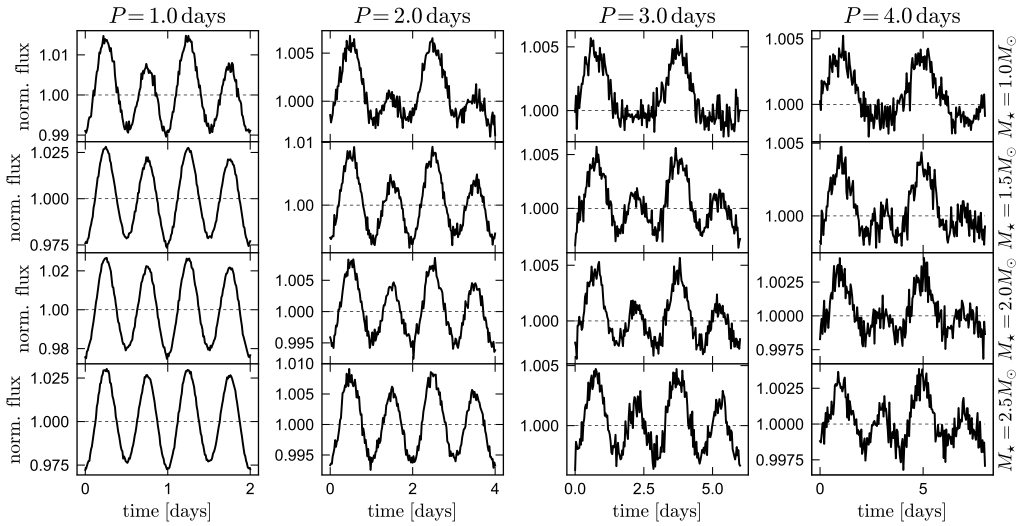


Figure 1: Synthetic TESS light curves for a $10\,M_\odot$ black hole and luminous main-sequence companions with a range of periods (columns) and masses (rows). For these periods and masses, ellipsoidal modulation and Doppler beaming produce approximately sinusoidal brightness variations with comparable amplitude. The predicted light curves have a easily-recognizable shape, with higher– and lower–amplitude peaks alternating once per orbital period. We have identified $\sim$ 150 targets with this light curve shape, from 10M TESS light curves. In addition to these targets, we will observe longer-period BH binary candidates selected from *Gaia* DR3 astrometry.

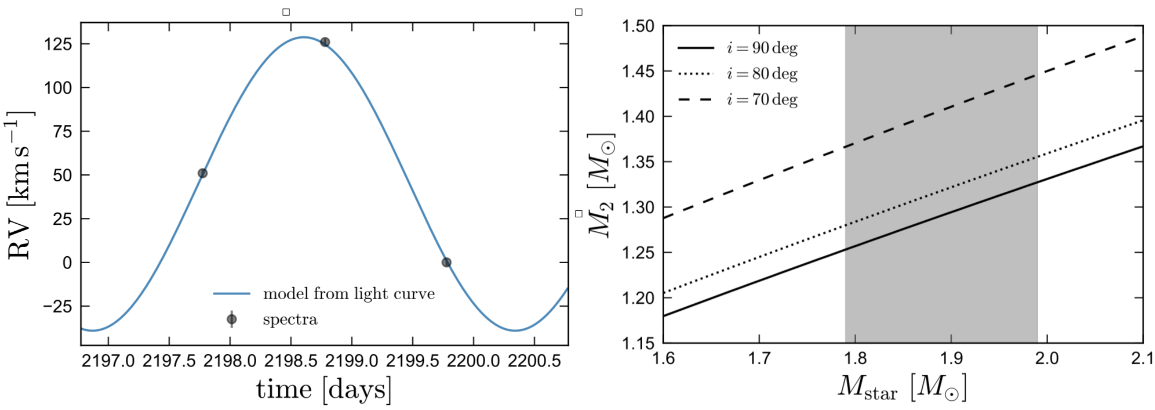


Figure 2: One of the targets from our pilot study in P106. Blue line shows the RV *prediction* based on the Doppler beaming observed in the TESS light curve (not shown). Black points show measured FEROS RVs, which are in excellent agreement with the light curve prediction. Right panel shows the dynamically implied mass of the dark companion, for a range of luminous star masses and inclinations. The mass of the dark companion is at least $1.3 M_\odot$, making it either a neutron star or one of the most massive white dwarfs ever discovered and a SNe Ia progenitor.

9. Objects to be observed

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

| Designation | $\alpha$ (2000) | $\delta$ (2000) | magnitude in spectral range to be observed | priority |
|---|---|---|---|---|
| 6689633355633313152 | $19^h\,40^m\,11.31^s$ | $-40°\,52'\,32.02''$ | 9.43 | 1 |
| 5764516710246109568 | $09^h\,01^m\,38.56^s$ | $-00°\,34'\,53.01''$ | 7.77 | 1 |
| 2883152898029041536 | $06^h\,02^m\,25.80^s$ | $-39°\,18'\,37.67''$ | 8.97 | 1 |
| 3522214379217895936 | $12^h\,42^m\,56.77^s$ | $-17°\,53'\,50.15''$ | 9.66 | 1 |
| 4804958898209625728 | $05^h\,52^m\,55.37^s$ | $-40°\,26'\,05.62''$ | 13.42 | 1 |
| 4960519040257342080 | $01^h\,37^m\,18.57^s$ | $-40°\,10'\,38.57''$ | 8.09 | 1 |
| 6399029099515454592 | $21^h\,55^m\,26.09^s$ | $-65°\,20'\,36.90''$ | 12.14 | 1 |
| 4957938623904615808 | $02^h\,05^m\,43.36^s$ | $-41°\,10'\,50.67''$ | 8.38 | 1 |
| 2472536054386810624 | $00^h\,56^m\,54.18^s$ | $-11°\,21'\,22.18''$ | 9.87 | 1 |
| 4800826173301650560 | $05^h\,14^m\,46.81^s$ | $-42°\,07'\,27.03''$ | 12.00 | 1 |
| 5737340257437103360 | $08^h\,58^m\,43.63^s$ | $-11°\,03'\,12.41''$ | 12.88 | 1 |
| 6467196110314804096 | $20^h\,24^m\,49.72^s$ | $-59°\,57'\,53.73''$ | 8.39 | 1 |
| 3784490302359916800 | $11^h\,06^m\,56.09^s$ | $-07°\,07'\,51.61''$ | 12.10 | 1 |
| 3214736811504531072 | $05^h\,07^m\,34.87^s$ | $-02°\,43'\,57.71''$ | 10.17 | 1 |
| 6764584937292451200 | $19^h\,34^m\,41.27^s$ | $-28°\,50'\,26.56''$ | 9.21 | 1 |
| 2961956786178271616 | $05^h\,23^m\,05.65^s$ | $-21°\,37'\,09.46''$ | 11.02 | 1 |
| 6419852239137386880 | $18^h\,47^m\,20.82^s$ | $-69°\,56'\,37.73''$ | 12.54 | 1 |
| 2956582820017690880 | $05^h\,14^m\,39.82^s$ | $-25°\,08'\,13.46''$ | 10.35 | 1 |
| 5009058664692360448 | $01^h\,34^m\,06.82^s$ | $-38°\,15'\,23.26''$ | 11.93 | 1 |
| 2910725518619836928 | $05^h\,56^m\,59.14^s$ | $-26°\,50'\,08.29''$ | 12.01 | 1 |
| 3512478341192897024 | $13^h\,07^m\,48.32^s$ | $-15°\,43'\,30.71''$ | 11.51 | 1 |
| 3830431020608759552 | $10^h\,19^m\,23.55^s$ | $-01°\,28'\,46.45''$ | 11.20 | 1 |
| 6160112373920233088 | $12^h\,36^m\,10.50^s$ | $-32°\,56'\,52.24''$ | 11.34 | 1 |
| 2990059272590867072 | $05^h\,15^m\,51.25^s$ | $-10°\,49'\,34.53''$ | 10.89 | 1 |
| 4628962511493320960 | $03^h\,45^m\,08.90^s$ | $-75°\,14'\,20.28''$ | 11.49 | 1 |
| 5168468506186910592 | $03^h\,27^m\,41.42^s$ | $-07°\,59'\,41.68''$ | 13.00 | 1 |
| 3466791945137514368 | $11^h\,57^m\,03.68^s$ | $-33°\,18'\,55.73''$ | 6.17 | 1 |
| 5682843994398458112 | $09^h\,16^m\,41.84^s$ | $-16°\,50'\,13.22''$ | 8.54 | 1 |
| 3547999331345345280 | $11^h\,29^m\,13.84^s$ | $-17°\,21'\,04.17''$ | 8.41 | 1 |
| 3181464627575315840 | $04^h\,52^m\,47.62^s$ | $-10°\,47'\,45.71''$ | 10.97 | 1 |
| 2963678037271712384 | $05^h\,34^m\,30.55^s$ | $-23°\,31'\,41.21''$ | 8.34 | 1 |
| 4659083392032688512 | $05^h\,52^m\,59.81^s$ | $-68°\,26'\,33.36''$ | 9.66 | 1 |
| 4791084710733820160 | $04^h\,25^m\,46.50^s$ | $-44°\,51'\,15.46''$ | 7.54 | 1 |
| 5012685884833420800 | $01^h\,23^m\,03.69^s$ | $-37°\,22'\,29.18''$ | 12.90 | 1 |
| 4781801156103428096 | $04^h\,15^m\,22.03^s$ | $-51°\,44'\,26.87''$ | 10.09 | 1 |
| 4618082942718574464 | $02^h\,15^m\,49.63^s$ | $-82°\,30'\,48.13''$ | 8.96 | 1 |
| 3465457623352622848 | $11^h\,47^m\,05.75^s$ | $-33°\,35'\,34.38''$ | 8.02 | 1 |
| 6632914227977416960 | $18^h\,47^m\,22.91^s$ | $-60°\,22'\,30.63''$ | 7.45 | 1 |
| 6160037813289170944 | $12^h\,40^m\,42.15^s$ | $-32°\,40'\,02.35''$ | 9.71 | 1 |
| 3183829024251735040 | $05^h\,02^m\,48.68^s$ | $-08°\,12'\,34.03''$ | 7.78 | 1 |
| 6690579043008349312 | $19^h\,53^m\,15.65^s$ | $-39°\,24'\,35.22''$ | 9.57 | 1 |
| 6451418943089886080 | $21^h\,21^m\,03.40^s$ | $-63°\,03'\,32.05''$ | 9.37 | 1 |
| 6650451541516035584 | $18^h\,50^m\,06.95^s$ | $-54°\,27'\,47.33''$ | 7.95 | 1 |
| ~150 candidates total | $00^h\,00^m\,00^s$ | $00°\,00'\,00''$ | 0 | 1 |

10. `Justification of the amount of observing time requested:`

We want to measure multi-epoch RVs as well as atmospheric parameters, rotation rate, and chemical abundances ($T_{\rm eff}$, $\log g$, $v \sin i$ [Fe/H], [Xe/Fe]). According to the exposure time calculator (and verified in our pilot study), at $G = 11$, we can reach S/N=50 with 10 minute exposures. We require 3 exposures per object for ∼150 targets (exact number depends on the yields of *Gaia* DR3), plus additional exposures for the most promising targets after 3 RVs. At 20 minutes per epoch (including ∼5 minutes overhead, with some variation depending on source brightness and airmass), this will take ∼ 140 hours; i.e., 14 nights.

11. `Constraints for scheduling observations for this application:`

We would like our observations scheduled in June or later, so we can select additional targets from *Gaia* DR3. Our targets are distributed approximately uniformly in RA; we will choose which ones to observe based on the observing dates awarded. Roughly 70% of the targets are observable on any given night in the spring or summer. To maximize the number of targets we can observe, it would be ideal for our observations to be spread out somewhat (e.g., a week in June/July and a week in August/September).

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; with added funds from the GC department for service observing.

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 |
|---|---|---|---|---|---|
| 2.2m | FEROS | Dec 20 | 60 | 80% | in prep |
| 2.2m | FEROS | Aug 21 | 100 | 50% | in prep |

14. References for items 8 and 13:


[1] Brown, G. E., & Bethe, H. A. 1994, ApJ, 423, 659

[2] Mashian, N., & Loeb, A. 2017, MNRAS, 470, 2611

[3] Breivik, K., et al. 2017, ApJL, 850, 13

[4] Giesers, B., et al. 2018, MNRASL, 475, 15

[5] Khokhlov, S. A., et al. 2018, ApJ, 856, 158

[6] Thompson, T., et al. 2018, Science, 366, 637

[7] Rivinius, T., et al. 2020, A&A, 637, L3

[8] Jayasinghe, T., et al. 2021, Arxiv, 2101.02212

[9] Shao, Y., & Li, X.-D. 2019, accepted to ApJ

[10] Masuda, K., $ Hotokezaka, K. 2019, ApJ, 883, 169

[11] Abt, H., & Snowden, M.S. 1973, ApJS, 25, 137

[12] Cui, X.-Q., et al. 2012, RAA, 12, 1197

[13] Ricker, G., et al. 2015, SPIE, 1, 014003

[14] Andrews, J., et al. 2019, accepted to ApJ

[15] El-Badry, K. et al. 2018, MNRAS, 476, 528

[16] Rix, H.-W., et al. 2016, ApJL, 826, 25

[17] El-Badry, K. et al. 2019, MNRAS, 489, 5822

[18] Rix, H.-W., & Bovy, J. 2013, A%AR, 21, 61

[19] Zheng, L.-L. et al. 2019, accepted to AJ

[20] Gu, W.-M. et al. 2019, ApJL, 872, 20

[21] Yi, T. et al. 2019, accepted to ApJ

[22] Casares, J., et al. 2014, Nature, 505, 378

[23] Kalogera, V., & Webbink, R.F. 1998, ApJ 493, 351

[24] Prsa, A., & Zwitter, T. 2005, ApJ, 628, 426

[25] Chawla, C., et al. 2021, Arxiv, 2110.05979

**Tolerance limits for planned observations:**

| | | | | | |
|---|---|---|---|---|---|
| **maximum seeing:** | $4''$ | **minimum transparency:** | 50% | **maximum airmass:** | 2 |
| **photometric conditions:** | no | **moon: max. phase / ∠ :** | $1/20^\circ$ | **min. / max. lag:** | 1/60 nights |