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 2021 - March 2022
Received

APPLICATION FOR OBSERVING TIME

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

2.1 Applicant

Hans-Walter **Rix**	MPIA
Name	Institute
Königstuhl 17	D-69117 Heidelberg
street	ZIP code - city
RIX	rix@mpia.de
ESO User Portal username	e-mail

2.2 Collaborators

K. El-Badry; M. Xiang; S. Almada	MPIA/Harvard; MPIA; MPIA
name(s)	institute(s)
E. Quataert; D. Weisz; Y. Yang	Princeton; Berkeley; Yunnan Obs.
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* $G = 7 - 13.5$ mag), nearby ($d < 2$ kpc) stars that are candidates for having detached (non-accreting) black hole and neutron star companions with short periods ($P < 5$ days). Our targets were selected via their TESS light curves, which show evidence of Doppler beaming and tidal distortion. We will obtain 3 RVs for each target with a 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: .... 01.10.2021 – 31.03.2022
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 $\sim$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 "α" parameter) changes the number of predicted close BH-main sequence (MS) binaries by orders of magnitude [9]. 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] 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 $\sim$150 bright main-sequence stars selected based on light curve variability. From $\sim$5 million TESS "full frame image" light curves, we selected $\sim$150 with light curves showing evidence of both ellipsoidal modulation due to the tidal field of a companion, and relativistic Doppler beaming. For NS/BH+MS binaries with luminous-star masses $1-3\,M_\odot$ and orbital periods $1-5$ days, these two effects produce light curves with an easily-identifiable shape (e.g. Figure 1), which is not mimicked by binaries containing two ordinary stars, or by other kinds of common astrophysical variability.

Still, contaminants exist. Our pilot study in P106 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. To cut down on contaminants as much as possible, we limited our search to light curves of hot MS stars ($T_{\rm eff} > 6500$ K, where spots are less common) and performed a Fourier analysis to eliminate most pulsators.

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 enormous RV shifts from one night to the next, and our light curve models 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 not be as large as 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 $\sim$40 targets in P106, demonstrating the efficacy of our approach (Figure 2). The proposers have done extensive work in the most relevant area: reducing and modeling of stellar spectra to derive velocities and atmospheric parameters [15, 16]. We are also experienced in population modeling and statistical inference, which will be required to estimate the rate of BHs in binaries (or an upper limit) [17, 18].

Layout of observations

Our targets are distributed across the southern sky; on any given night in P108, about 70% are observable from La Silla at some point in the night. To maximize the number of targets we can observe, we request that our observations are spread out somewhat (e.g., a week in Oct/Nov and a week in Feb/March). It is not critical that nights be consecutive. In most cases, 3 epochs of RVs and a TESS light curve are 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). 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.

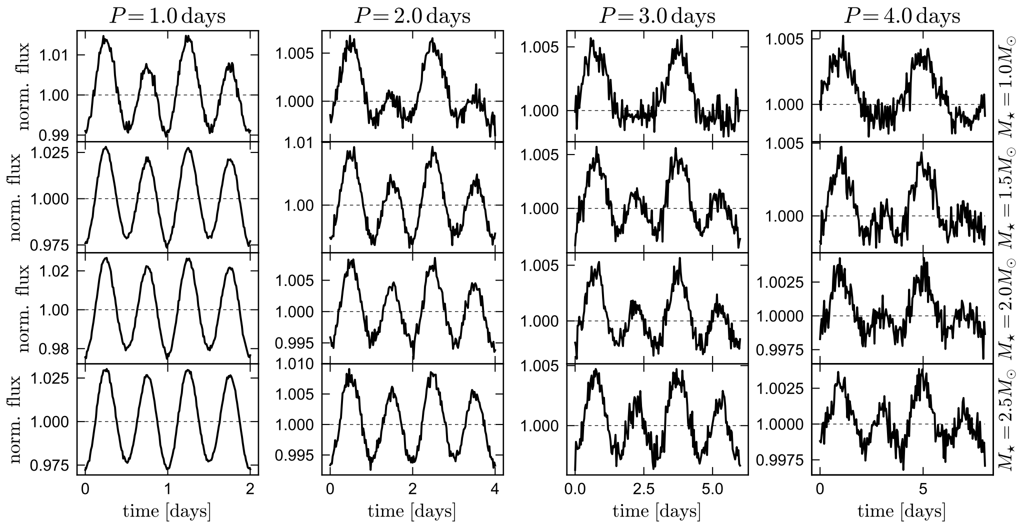

Figure 1: Synthetic TESS light curves for a $10\,M_\odot$ black hole and luminous main-sequence companions with a range of periods (columns) and masses (rows). For these periods and masses, ellipsoidal modulation and Doppler beaming produce approximately sinusoidal brightness variations with comparable amplitude. Because the period of ellipsoidal variability is half that of beaming, the predicted light curves have a easily-recognizable shape, with higher– and lower–amplitude peaks alternating once per orbital period. We have searched the TESS light curves of ∼5 million main-sequence stars and identified ∼ 150 targets with this light curve shape.

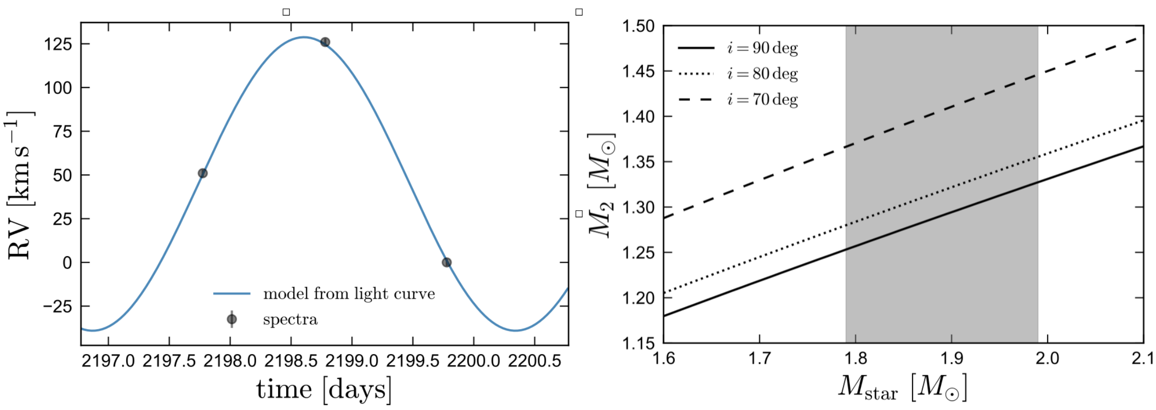

Figure 2: One of the targets from our pilot study in P106. Blue line shows the RV *prediction* based on the Doppler beaming observed in the TESS light curve (not shown). Black points show measured FEROS RVs, which are in excellent agreement with the light curve prediction. Right panel shows the dynamically 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	α (2000)	δ (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, 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:

No strong constraints. 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 fall or winter. 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 Oct/Nov and a week in Feb/March).

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

We anticipate service observing under the new agreement; 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%	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

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