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 2020 - March 2021
Received	

APPLICATION FOR OBSERVING TIME

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

1. Telescope: 2.2-m [X]

2.1 Applicant

Hans-Walter **Rix**	MPIA
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Königstuhl 17	D-69117 Heidelberg
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ESO User Portal username	e-mail

2.2 Collaborators

K. Nielsen; M. Xiang; K. El-Badry	MPIA; MPIA; Berkeley
name(s)	institute(s)
E. Quataert; D. Weisz; Y. Yang	Berkeley; 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 in binaries**

Abstract : We propose FEROS spectroscopy to measure multi-epoch radial velocities (RVs) for a sample of ∼200 bright (*Gaia* $G = 7-13.5$ mag), nearby ($d < 2$ kpc) stars that are candidates for having detached (non-accreting) black hole (BH) companions with short periods ($P < 5$ days). We will obtain 2-5 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 population of Galactic stellar mass black holes that are not accreting 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: .... 01.10.2020 – 03.31.2021
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 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], but their status as BHs is not unambiguous, and the detached BH binary population 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 low-mass 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 (WFIRST), and multi-epoch RVs (SDSS V), but these waters are thus far still uncharted.

Theoretical predictions for BH binary population statistics disagree considerably between models. Varying the fraction of a binary's orbital energy that is coupled to the envelope of the BH progenitor during common envelope evolution changes the number of predicted close BH-main sequence (MS) binaries by two orders of magnitude [8]. 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 low.

Even if our search returns no BHs, the resulting lower limits will yield strong constraints on evolutionary models. Recently, [9] and [20] carried out population synthesis simulations to determine specifically how many detached BH-MS binaries should be discoverable via our search strategies. They predicted that more than 400 such binaries should have already been observed by surveys. 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 two samples of BH binary candidates.

(a) The first set is selected based on TESS light curves: we identified $\sim$ 200 stars with light curves showing evidence of both ellipsoidal modulation due to the tidal field of a companion and relativistic Doppler beaming. For BH–MS binaries with a range of primary masses ($1 < M/M_\odot < 3$) and periods ($1 < P/\text{days} < 5$), these two effects produce light curves with an easily-identifiable shape, which is not mimicked by binaries containing two ordinary stars (see [9] and Figure 1). We limited our search to light curves of hot MS stars ($M > 1.5 M_\odot$ and $T_{\rm eff} > 6500\,\mathrm{K}$) in order to minimize contamination from rapidly rotating spotted stars. We also excluded the Galactic plane in our search, so that background contamination is usually negligible.

We propose to obtain two epochs of RVs, separated by at least one night, for each of these targets. We expect that rapidly-rotating AP and BP stars are the main contaminant. Such stars have a frozen-in dipole magnetic field and thus often have two dominant and stable spot complexes, despite being hotter than 6500 K; this can lead to light curves similar to those produced by ellipsoidal variation and beaming in binaries. Two epochs of RVs will be sufficient to eliminate these contaminants: while genuine BH binaries will exhibit large velocity variations between epochs, AP and BP stars will not: most are single [10].

(b) An additional set of 20 candidates was obtained by searching for short-timescale RV variability in the LAMOST survey [11]. For $\sim$ 6 million LAMOST targets, we re-reduced the single-exposure spectra which are co-added to produce the final LAMOST spectrum and identified targets with statistically significant RV shifts between exposures (typically separated by 20 minutes) as probable short-period binaries. We obtained light curves for these targets from TESS, allowing the orbital period to be measured from ellipsoidal variability. Combining this period with the acceleration measured from LAMOST yields a lower limit on the companion mass (Figure 2). We propose to obtain follow-up RVs for candidates where this lower limit exceeds the mass of the luminous star.

Previous work

An earlier version of this proposal was approved for spring 2020, but the observations did not take place due to COVID-19. The proposers have done extensive work in the most relevant area: reducing and modeling of stellar spectra to derive velocities and atmospheric parameters [14, 15]. 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) [16, 17].

Layout of observations

For candidates identified from TESS with no RV measurements thus far, we require two RV epochs on different nights to confirm or rule out the large RV variation expected for genuine binaries. For the candidates that already have detected RV variability from LAMOST, we require 5 additional RVs. In these cases, joint modeling of the RVs and light curves will fully constrain the orbit.

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 thesis of CO-I K. Nielsen.

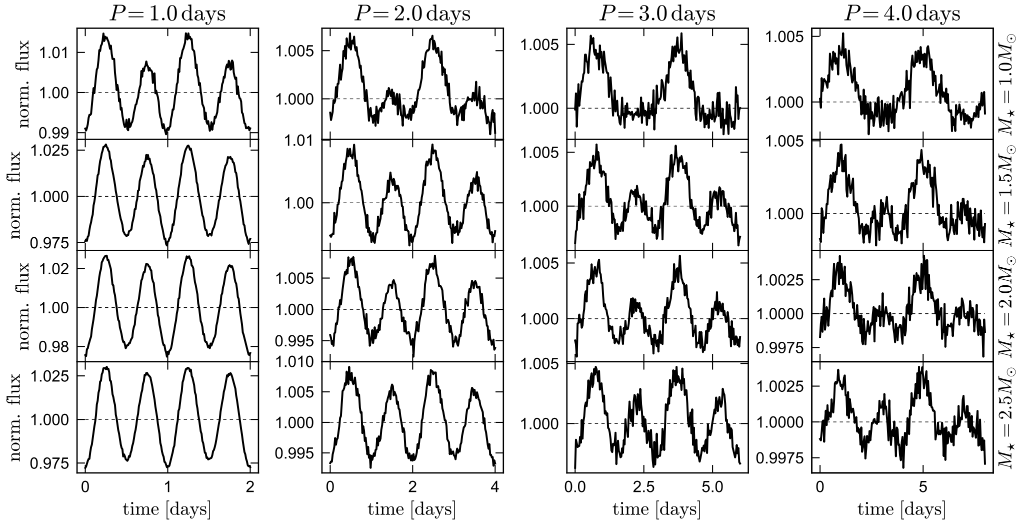

Figure 1: Synthetic TESS light curves for a $10\,M_\odot$ black hole and luminous main-sequence companions with a range of periods (columns) and masses (rows). For these periods and masses, ellipsoidal modulation and Doppler beaming produce approximately sinusoidal brightness variations with comparable 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 ~600,000 main-sequence stars with $M > 1.5 M_\odot$ and identified ~ 200 targets with this light curve shape.

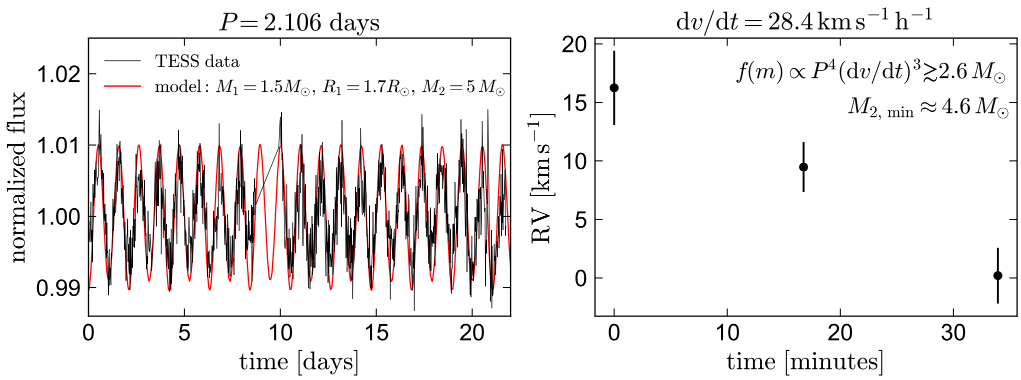

Figure 2: Left panel shows the TESS light curve and best-fit model for a target from the LAMOST sample. Right panel shows RVs from three single-exposure LAMOST spectra, each separated by 17 minutes. The RV shift between exposures yields an instantaneous acceleration, $\mathrm{d}v/\mathrm{d}t$. This can be combined with the photometric period, yielding a lower limit on the mass function, $f(m)$, and on the mass of the companion, $M_{2,\mathrm{min}} \approx 4.6 M_\odot$. Because there is no evidence of a companion in the spectra or photometry, these data suggest it is a BH.

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
∼200 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 and rotation rate ($v \sin i$). According to the exposure time calculator, at $G = 11$, we will reach S/N=50 with 10 minute exposures. We require 2 exposures per object for $\sim$ 200 targets, plus 5 exposures per object for the 20 targets identified from LAMOST. At 15 minutes per epoch (including $\sim$5 minutes overhead, with some variation depending on G-band magnitude), this will take $\sim$ 140 hours; i.e., 14 nights.

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

No constraints. Our targets are distributed approximately uniformly in RA; we will choose which ones to observe based on the observing dates awarded. Roughly 75% of the targets are observable on any given night in the fall or winter.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[23] 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