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	P107
Received	

APPLICATION FOR OBSERVING TIME

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

1. Telescope: 2.2-m [X]

2.1 Applicant

Dr Richard **Anderson**	Max-Planck-Insitute for Astronomy
Name	Institute
Königstuhl 17	69117 Heidelberg
street	ZIP code - city
rianders	anderson@mpia.de
ESO User Portal username	e-mail

2.2 Collaborators

name(s)	institute(s)
name(s)	institute(s)

2.3 Observers

Richard Anderson	
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 : **Time-series spectroscopy of Galactic Cepheids with FEROS**

Abstract : We request time-series spectroscopic observations of a large sample of Galactic classical Cepheid variable stars. Program stars have been selected based on unpublished results from a large Cepheid radial velocity program led by the PI, e.g. using the Swiss Euler telescope at La Silla. The goal of these observations is to detect or measure orbital motion, cycle-to-cycle variations, long-term modulations, multi-periodic line profile variations, and more. FEROS at the 2.2m MPG telescope is uniquely suited for this project due to the access modalities, wavelength coverage, resolution, sensitivity, and wavelength solution stability. These observations will support the calibration of extragalactic distances and provide new insights into the physics and structure of Cepheids.

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

5. Brightness range of objects to be observed: from 3 to 14 V-mag

6. Number of hours:

applied for			already awarded	still needed
200			0	1800
no restriction	grey	dark		

7. Optimum date range for the observations: .... 1.1.21 – 30.9.21
Usable range in local sideral time LST: .... h – h

Astrophysical context

Classical Cepheids (henceforth: Cepheids) are evolved intermediate-mass ($4-11\,M_\odot$) yellow (super-)giant stars that feature high-amplitude radial pulsations resulting in striking and complex spectroscopic variability. Recent research has revealed line profile variations on timescales different from the main pulsation period [1][2], possibly indicating non-radial pulsations and real-time hydrodynamic effects such as pulsation-convection coupling [3], cf. Fig. 2. Densely phase-sampled high-resolution spectroscopic time-series observations are required to dig deeper into these phenomena and explore the long-term asteroseismic opportunities for Cepheids [4]. As a first step in this direction, this proposal seeks to search for periodicity among spectral line variability not associated with the main radial pulsation mode.

Cepheids feature phase-dependent velocity gradients that contribute to spectral line asymmetry and cause spectral lines of different species to move at different velocities [3]. Nearly all previously published Cepheid radial velocities (RVs) were based on Doppler shifts of optical spectral lines. However, the ESA mission *Gaia*/RVS instrument observes in a narrow region near the infrared Calcium triplet, where RV amplitudes and spectral line asymmetries could be significantly different from those seen among optical spectral lines [5]. Here, we will use FEROS to investigate atmospheric velocity gradients and line asymmetry differences between the two spectral domains as a function of stellar parameters (e.g. period). This will allow us to quantify any resulting biases in amplitude or systemic velocities (v_γ).

Last, but not least, Cepheids are of crucial importance to cosmology in their role as standard candles for distance ladder calibration thanks to the period-luminosity relation (PLR, Leavitt law). Companion stars can cause complications through several channels [6]: a) they can affect parallax measurements [7] (NB: Gaia EDR3 will feature only single star astrometric solutions), b) they contribute additional light not accounted for in theoretically predicted Leavitt laws, c) the occurrence rate of binaries may be depend on environment, e.g. Cepheids in star clusters vs. the field. Moreover, binaries enable mass measurements [8]. Mass measurements are urgently needed to understand and resolve the mass discrepancy, which denotes the failure of stellar models to correctly predict Cepheid masses at the level of $10-20\%$ [9]. In turn, the mass discrepancy also implies a failure of stellar models to correctly predict the PLR from first principle because this requires an accurate mass-luminosity-relation [10].

Immediate aims

Using FEROS@MPG2.2m, the observations requested here aim to:

1. lay the ground-work for a long-term monitoring program of Cepheids with FEROS
2. detect modulated spectral line variability in Cepheids using FEROS, e.g. via line bisectors, cf. Fig. 3
3. detect cycle-to-cycle variations in long-period Cepheids (with periods up to 70d); for this a minimum of two successive cycles must be closely followed, cf. Fig. 2
4. measure radial velocities of Cepheids in the commonly used optical wavelength range and near the Ca II infrared triplet for comparison with future *Gaia*/RVS time series
5. determine periodicity on timescales of $<$ 6 months for Cepheids known to exhibit modulated spectral line variability
6. measure long-period ($\sim 10+$ yr) orbits of Galactic Cepheids in combination with data previously collected by the PI, cf. Fig. 1. Some program stars are part of an *HST/STIS* project (PI: N. R. Evans) to measure Cepheid masses in case companion lines are seen in the UV.
7. provide high-resolution, high signal-to-noise, densely phase-sampled spectroscopic time series for further detailed analysis

Previous work

My previous work, for example, using the Swiss Euler telescope at La Silla, has demonstrated the occurrence of the puzzling spectral variability in Cepheids [1, 2, 3], cf. Figs. 2&3. This proposal builds on and complements this project to investigate long-term variability modulations that began in 2011.

Layout of observations

The observations can be gathered in service mode, visitor mode, or remotely. Although program stars differ in required observational cadence, most objects are very easily scheduled as filler objects whenever the loose observing conditions are met. Observations with a simultaneous wavelength reference, such as a ThAr lamp or Fabry-Pérot etalon, are required for maximum wavelength solution stability. Cadences per object vary greatly because the proposal seeks to study modulations of pulsations with periods ranging from about 2 d to 60 d.

Strategic importance for MPIA

These observations are a crucial part of the new ERC-STG project H1PStars (PI: R.I. Anderson) at MPIA. These FEROS observations are part of the institute contribution commitment to that group (from GC department resources).

8b. Figures and tables

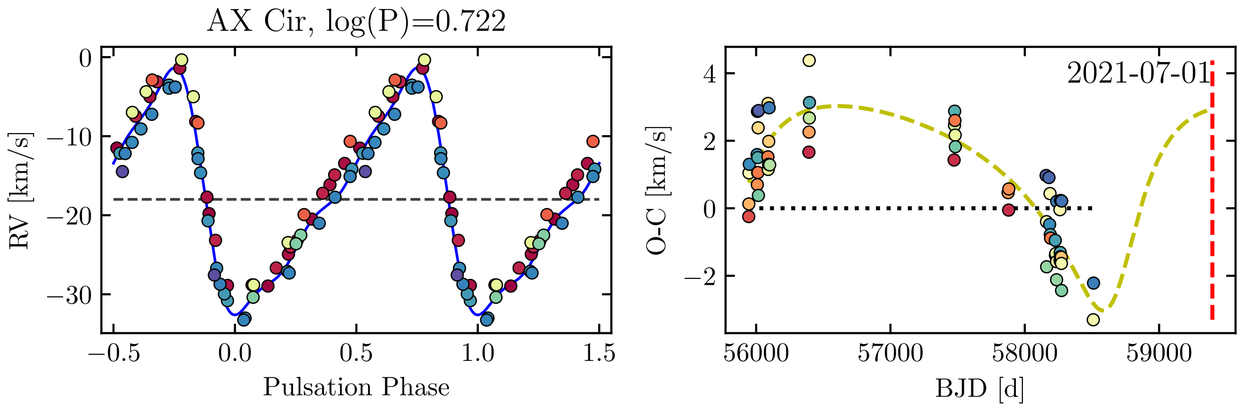

Figure 1: Example binary Cepheid. Left: pulsation. Right: orbit & preliminary fit, P107 shown in red.

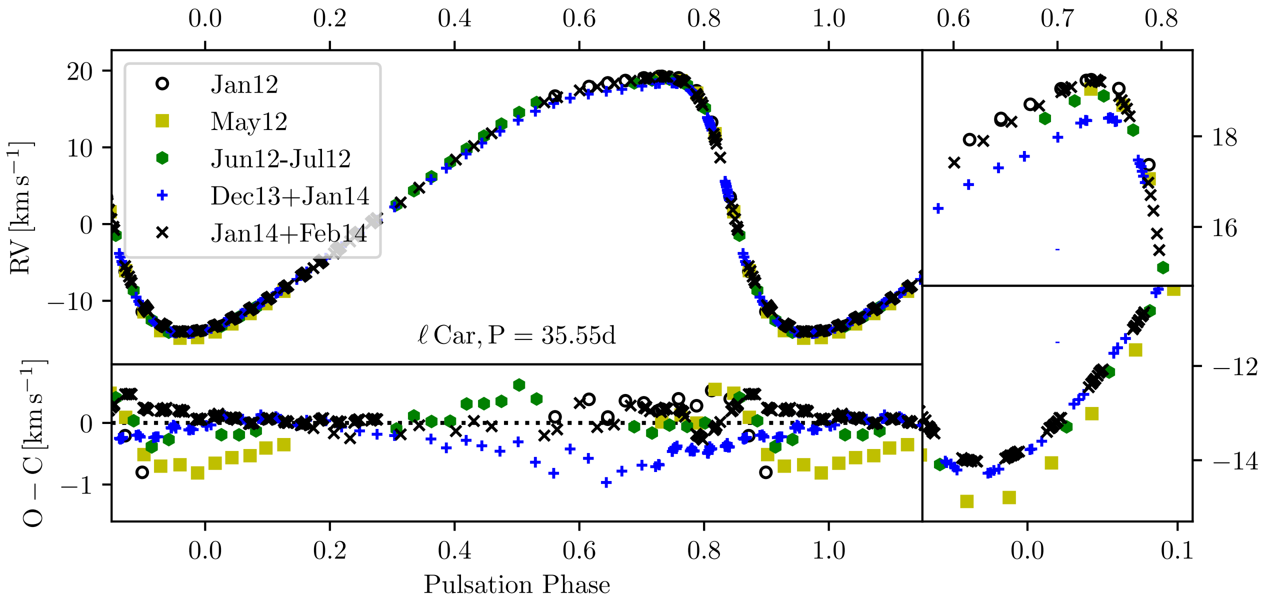

Figure 2: Example cycle-to-cycle variation in long-period Cepheid [1].

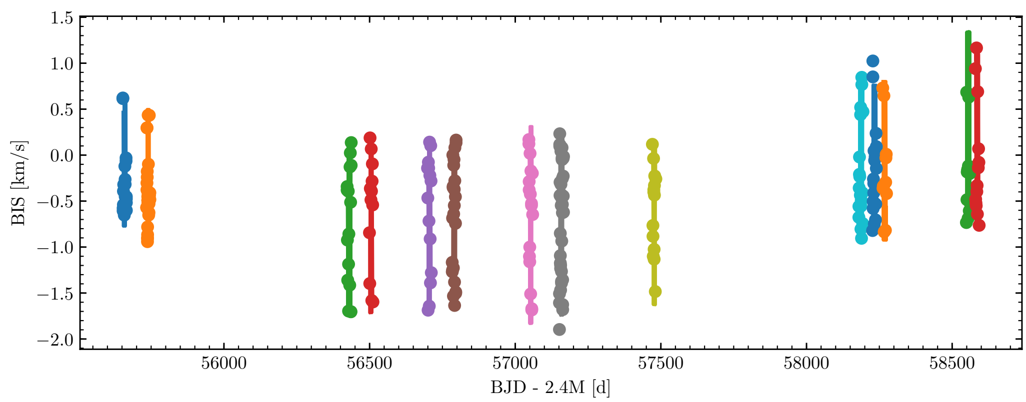

Figure 3: Example of long-term line bisector variations in short-period Cepheids [4]

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
TX Mon	$06^{h}\,50^{m}\,52^{s}.2$	$-01^\circ\,25'\,45''$	11.04	highest
TZ Mon	$06^{h}\,58^{m}\,00^{s}.9$	$-00^\circ\,22'\,33''$	10.84	medium
AO CMa	$07^{h}\,24^{m}\,40^{s}.5$	$-26^\circ\,11'\,19''$	12.08	medium
X Pup	$07^{h}\,32^{m}\,47^{s}.0$	$-20^\circ\,54'\,35''$	8.57	low
WX Pup	$07^{h}\,41^{m}\,58^{s}.9$	$-25^\circ\,52'\,34''$	9.13	low
AD Pup	$07^{h}\,48^{m}\,03^{s}.8$	$-25^\circ\,34'\,40''$	9.86	high
NT Pup	$07^{h}\,58^{m}\,46^{s}.2$	$-38^\circ\,59'\,40''$	11.89	highest
V Car	$08^{h}\,28^{m}\,43^{s}.6$	$-60^\circ\,07'\,21''$	7.48	high
SW Vel	$08^{h}\,43^{m}\,38^{s}.6$	$-47^\circ\,24'\,11''$	8.17	highest
ASAS J084951-4627.2	$08^{h}\,49^{m}\,51^{s}.0$	$-46^\circ\,27'\,12''$	11.27	highest
FN Vel	$09^{h}\,48^{m}\,41^{s}.4$	$-55^\circ\,31'\,10''$	10.3	high
GX Car	$09^{h}\,55^{m}\,26^{s}.1$	$-58^\circ\,25'\,47''$	9.39	highest
V0397 Car	$10^{h}\,00^{m}\,03^{s}.6$	$-66^\circ\,16'\,34''$	8.33	medium
RY Vel	$10^{h}\,20^{m}\,41^{s}.0$	$-55^\circ\,19'\,17''$	8.4	highest
YZ Car	$10^{h}\,28^{m}\,16^{s}.8$	$-59^\circ\,21'\,\ 1''$	8.69	high
ASAS J103158-5814.7	$10^{h}\,31^{m}\,58^{s}.0$	$-58^\circ\,14'\,42''$	11.38	highest
CR Car	$10^{h}\,32^{m}\,54^{s}.0$	$-58^\circ\,31'\,16''$	11.62	medium
HW Car	$10^{h}\,39^{m}\,20^{s}.3$	$-61^\circ\,09'\,\ 9''$	9.16	medium
XX Car	$10^{h}\,57^{m}\,09^{s}.2$	$-65^\circ\,08'\,\ 5''$	9.33	medium
U Car	$10^{h}\,57^{m}\,48^{s}.1$	$-59^\circ\,43'\,56''$	6.4	high
IT Car	$11^{h}\,12^{m}\,10^{s}.1$	$-61^\circ\,45'\,17''$	8.11	highest
KK Cen	$11^{h}\,42^{m}\,48^{s}.2$	$-58^\circ\,59'\,36''$	11.43	medium
UU Mus	$11^{h}\,52^{m}\,17^{s}.7$	$-65^\circ\,24'\,15''$	9.75	medium
V0659 Cen	$13^{h}\,31^{m}\,33^{s}.4$	$-61^\circ\,34'\,56''$	6.59	highest
VW Cen	$13^{h}\,33^{m}\,59^{s}.0$	$-64^\circ\,03'\,20''$	10.24	low
KN Cen	$13^{h}\,36^{m}\,36^{s}.8$	$-64^\circ\,33'\,30''$	9.92	high
AX Cir	$14^{h}\,52^{m}\,35^{s}.2$	$-63^\circ\,48'\,35''$	5.89	high
GS Lup	$14^{h}\,55^{m}\,15^{s}.4$	$-54^\circ\,03'\,17''$	10.48	highest
LR TrA	$15^{h}\,30^{m}\,49^{s}.8$	$-65^\circ\,35'\,58''$	7.83	highest
ASAS J155847-5341.8	$15^{h}\,58^{m}\,46^{s}.9$	$-53^\circ\,41'\,48''$	9.95	highest
QZ Nor	$16^{h}\,11^{m}\,20^{s}.4$	$-54^\circ\,21'\,15''$	8.88	highest
V0340 Ara	$16^{h}\,45^{m}\,19^{s}.1$	$-51^\circ\,20'\,33''$	10.22	low
KQ Sco	$16^{h}\,51^{m}\,38^{s}.5$	$-45^\circ\,25'\,36''$	9.83	highest
RV Sco	$16^{h}\,58^{m}\,19^{s}.7$	$-33^\circ\,36'\,33''$	7.09	high
V0636 Sco	$17^{h}\,22^{m}\,46^{s}.4$	$-45^\circ\,36'\,51''$	6.68	high
ASAS J173848-3304.4	$17^{h}\,38^{m}\,47^{s}.9$	$-33^\circ\,04'\,24''$	9.74	medium
ASAS J174108-2328.5	$17^{h}\,41^{m}\,08^{s}.0$	$-23^\circ\,28'\,30''$	9.5	medium
ASAS J174603-3528.1	$17^{h}\,46^{m}\,02^{s}.9$	$-35^\circ\,28'\,\ 6''$	10.8	highest
X Sgr	$17^{h}\,47^{m}\,33^{s}.6$	$-27^\circ\,49'\,51''$	4.58	highest
ASAS J180342-2211.0	$18^{h}\,03^{m}\,42^{s}.0$	$-22^\circ\,10'\,60''$	10.91	high
UZ Sct	$18^{h}\,31^{m}\,22^{s}.3$	$-12^\circ\,55'\,43''$	11.31	low
RU Sct	$18^{h}\,41^{m}\,56^{s}.3$	$-04^\circ\,06'\,38''$	9.44	low
ASAS J184741-0654.4	$18^{h}\,47^{m}\,41^{s}.1$	$-06^\circ\,54'\,24''$	9.07	highest
ASAS J190929+1232.8	$19^{h}\,09^{m}\,28^{s}.9$	$+12^\circ\,32'\,48''$	11.16	high
V1803 Aql	$19^{h}\,20^{m}\,06^{s}.9$	$+12^\circ\,47'\,43''$	10.39	high
U Vul	$19^{h}\,36^{m}\,37^{s}.7$	$+20^\circ\,19'\,59''$	7.17	highest
S Vul	$19^{h}\,48^{m}\,23^{s}.8$	$+27^\circ\,17'\,11''$	9.08	highest
SV Vul	$19^{h}\,51^{m}\,30^{s}.9$	$+27^\circ\,27'\,37''$	7.3	highest

10. Justification of the amount of observing time requested:

Precise spectroscopic long-term monitoring is required to resolve long-term changes (months to several years) of pulsation cycles as well as multi-year to decade-long orbital motion.
FEROS is perfectly suited to this project, since it provides the wavelength solution stability required to resolve even small cycle-to-cycle variations or long-term modulations, while covering both the typical wavelength range of "optical" radial velocities and the Ca II IR triplet observed by *Gaia*/RVS.
The ability to access the 2.2m MPG telescope flexibly around the year represents a unique opportunity for conducting long-term studies of spectral variability. Larger facilities, such as HARPS on the 3.6m ESO, or UVES on the VLT, are not suitable for this program due to extreme pressure from other projects.
The 200 hours requested correspond to 20n/semester of FEROS observations in support of the PI's group at the MPIA's GC department, assuming 10 hour nights (Southern Fall and Winter).
The target list shown in Section 9 above is a non-exhaustive, representative target list for program stars to be observed in P107.
Overheads of 300s per observation (pointing, focus, and read-out) have been assumed.

11. Constraints for scheduling observations for this application:

Scheduling constraints may vary from target to target, but are usually not time-critical. For example, most targets should be observed a certain number of nights in a row in order to sample pulsational variability while mapping longer-term trends. For example, V Car should be observed once per night over 7 consecutive nights at any time when it is visible.
Stars exhibiting long-term line profile changes, such as X Sgr, or long-period Cepheids exhibiting cycle-to-cycle variations should be observed nightly (or almost nightly) on most nights throughout the semester on a best-effort basis. The timing during the night is not important and should, indeed, be varied.
The PI will coordinate internally to ensure a relatively straightforward implementation of the varying constraints on cadence/number of observations. For example, this could be done via a program-specific website, or Google spreadsheet (tbd), or other.
In case of conflict with time critical observations, the more time critical observations can usually be given priority. In other words, the long-term monitoring in this program should not block other, time critical observations. In most cases, it will be straightforward to push an observation to the next night. Long-term monitoring targets should be given priority over other stars if little time is left in a given night.

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

The PI has nearly 300 nights of observational experience on the Swiss 1.2m Euler telescope at La Silla Observatory and the Flemish 1.2m Mercator telescope at Roque de los Muchachos Observatory on La Palma. The PI is an expert in Cepheid radial velocity observations and spectral variability.

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] Anderson (2014): *Tuning in on Cepheids: Radial velocity amplitude modulations. A source of systematic uncertainty for Baade-Wesselink distances*, A&A **566**, L10

[2] Anderson (2019b): *Probing Polaris' puzzling radial velocity signals. Pulsational (in-)stability, orbital motion, and bisector variations*, A&A **623**, A146

[3] Anderson et al. (2016a): *Discovery of Cycle-to-cycle Modulated Spectral Line Variability and Velocity Gradients in Long-period Cepheids*, MNRAS **463**, 1707

[4] Anderson (2020): *Cepheids under the magnifying glass - not so simple, after all!*, arXiv:2001.03028

[5] Wallerstein et al. (2019): *The Behavior of the Paschen and Calcium Triplet Lines in Cepheid Variables II: The 16-day Variable X Cygni*, PASP **131**, 4203

[6] Anderson & Riess (2018): *On Cepheid Distance Scale Bias Due to Stellar Companions and Cluster Populations*, ApJ **861**, 36

[7] Anderson (2016): *Vetting Galactic Leavitt Law Calibrators Using Radial Velocities: On the Variability, Binarity, and Possible Parallax Error of 19 Long-period Cepheids*, ApJS **226**, 18

[8] Evans et al. (2018): *The Mass of the Cepheid V350 Sgr*, ApJ **866**, 30

[9] Pilecki et al. (2018): *The Araucaria Project: High-precision Cepheid Astrophysics from the Analysis of Variables in Double-lined Eclipsing Binaries*, ApJ **862**, 43

[10] Anderson et al. (2016b): *On the effect of rotation on populations of classical Cepheids. II. Pulsation analysis for metallicities 0.014, 0.006, and 0.002*, A&A **591**, A8

Tolerance limits for planned observations:

maximum seeing:	2.5″	**minimum transparency:**	30%	**maximum airmass:**	2.2
photometric conditions:	no	**moon: max. phase / ∠ :**	1/30°	**min. / max. lag:**	/ nights