Relating spot and flare/superflare occurrence on dwarf stars

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UNIVERSITÄT GRAZ
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Master's Thesis

Relating spot and flare/superflare occurrence on dwarf stars

Markus Ornik

in partial fulfillment of the requirements for the degree of
Master of Science – MSc

Supervisors Assoz. Prof. Mag. Dr.rer.nat. Manuela Stadlober-Temmer
Mag. Dr.rer.nat. Martin Leitzinger

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Abstract

Context.

Aims.

Methods.

Results.

Conclusions.

Acknowledgement

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This research made use of pandas (team, 2020a; McKinney, 2010). This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al., 2013; Astropy Collaboration et al., 2018). This research made use of SciPy (Virtanen et al., 2020). This research made use of matplotlib, a Python library for publication quality graphics (Hunter, 2007). This research made use of NumPy (Harris et al., 2020a; Harris et al., 2020b). This research made use of Astroquery (Ginsburg et al., 2019).

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

This paper includes data collected by the Kepler mission and obtained from the MAST data archive at the Space Telescope Science Institute (STScI). Funding for the Kepler mission is provided by the NASA Science Mission Directorate. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5–26555.

This paper includes data collected with the TESS mission, obtained from the MAST data archive at the Space Telescope Science Institute (STScI). Funding for the TESS mission is provided by the NASA Explorer Program. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5–26555.

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Contents

Appendix

1 Introduction

1.1 Current knowledge

1.2 Spectral Types

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1.4 Space missions

Thompson et al. (2012).

Kepler 6

$$c^2 = a^2 + b^2, \quad (1.1)$$
$$c = \sqrt{a^2 + b^2}, \quad (1.2)$$

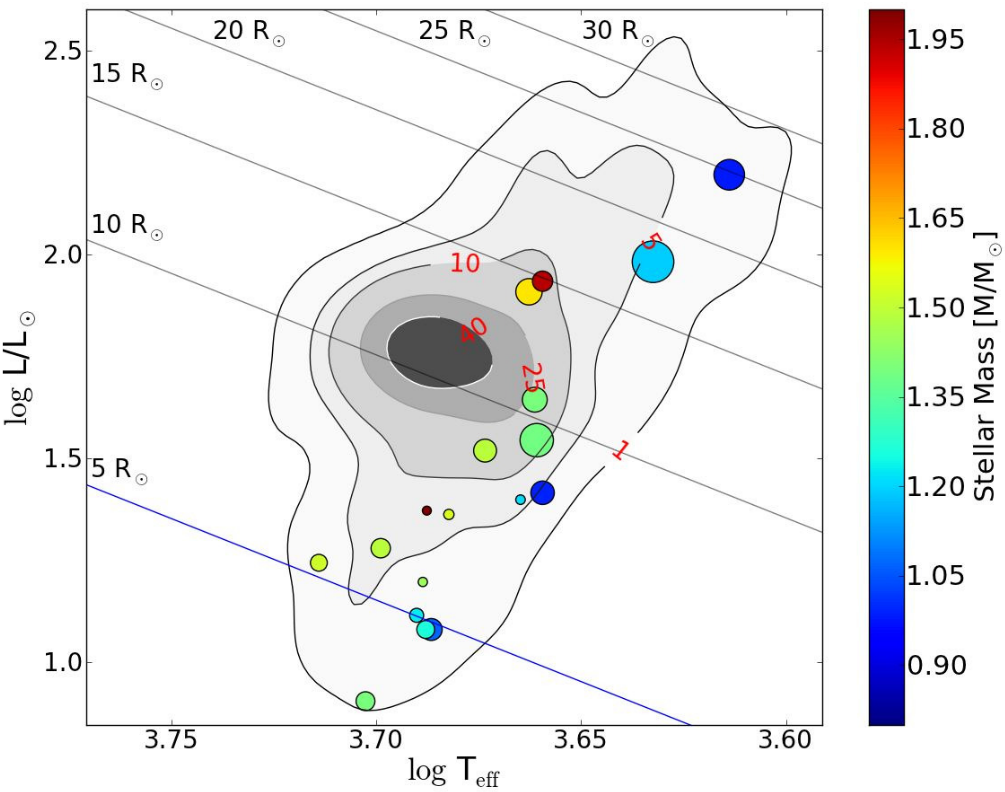

Fig. 1.1.: Position of the 18 red giant heartbeat stars from Tables 1 and 2 in the HR diagram, where the colour shows the mass of the red giant, derived from seismology. The size of the dots represents the orbital period, ranging between 20 and 438 d. The contour surfaces reflect the density distribution of 1000 pulsating red giants. The darkest areas mark the position of the densely populated red clump. Numbers in red indicate the star count per bin, for which the contour surfaces have been drawn. Lines of equal radii in the HR diagram have been drawn for selected stellar radii between 5 and 30 R. (Figure taken from Beck et al., 2014)

GUI

2

In this chapter the usage of the developed GUI application is explained. It was developed to easily download new data, as well as try various algorithms for flare detection and the usage of various functions of the lightkurve python package (Lightkurve Collaboration et al. (2018)).

2.1 Data download

During the first startup the GUI window (e.g. in figure 2.2) is nearly completely empty. An empty local database will be created with SQLite3 (SQLite Development Team (2025)). To show lightcurves, first data needs to be downloaded. For that, the "Add" button has to be clicked. A new dialog window will show. It can be seen in figure 2.1. This GUI uses the astroquery (Ginsburg et al. (2019)) python package to fetch metadata and download fits files from MAST (Mikulski Archive for Space Telescopes).
The first step is to enter the identifier of the star(s). In case of multiple, they have to be seperated by a semicolon. Then the missions from which the data should be fetched can be selected. The supported missions are TESS and Kepler/K2. For Kepler and K2 short and/or long cadence can be selected. The differeces are described in section 1.4. After the selection has been made, the fetch button needs to be pressed. The program will then request metadata matching the star identifier(s) and selected missions from the MAST archive. The found mission data is then displayed in the preview field. It can then be downloaded by pressing the "Ok" button. The program the proceeds to download the according fits-files. The filename and TESS sector or Kepler/K2 target table ID is appended to the previously fetched metadata and handed back to the main GUI.
There a request to Simbad is made to fetch additional metadata. First the alternative identifiers are fetched from Simbad, which also has a MAIN_ID attribute. This is to make sure we only have one entry in the local database per star and no duplicates. Afterwards additional data is fetched from Simbad (Wenger et al. (2000)) like spectral type, radial velocity and distance. After the data is gathered, the main identifier, the alternative identifiers, spectral type, rotational velocity and distance (and their respective units) as well as the file path, source (TESS, Kepler or K2),

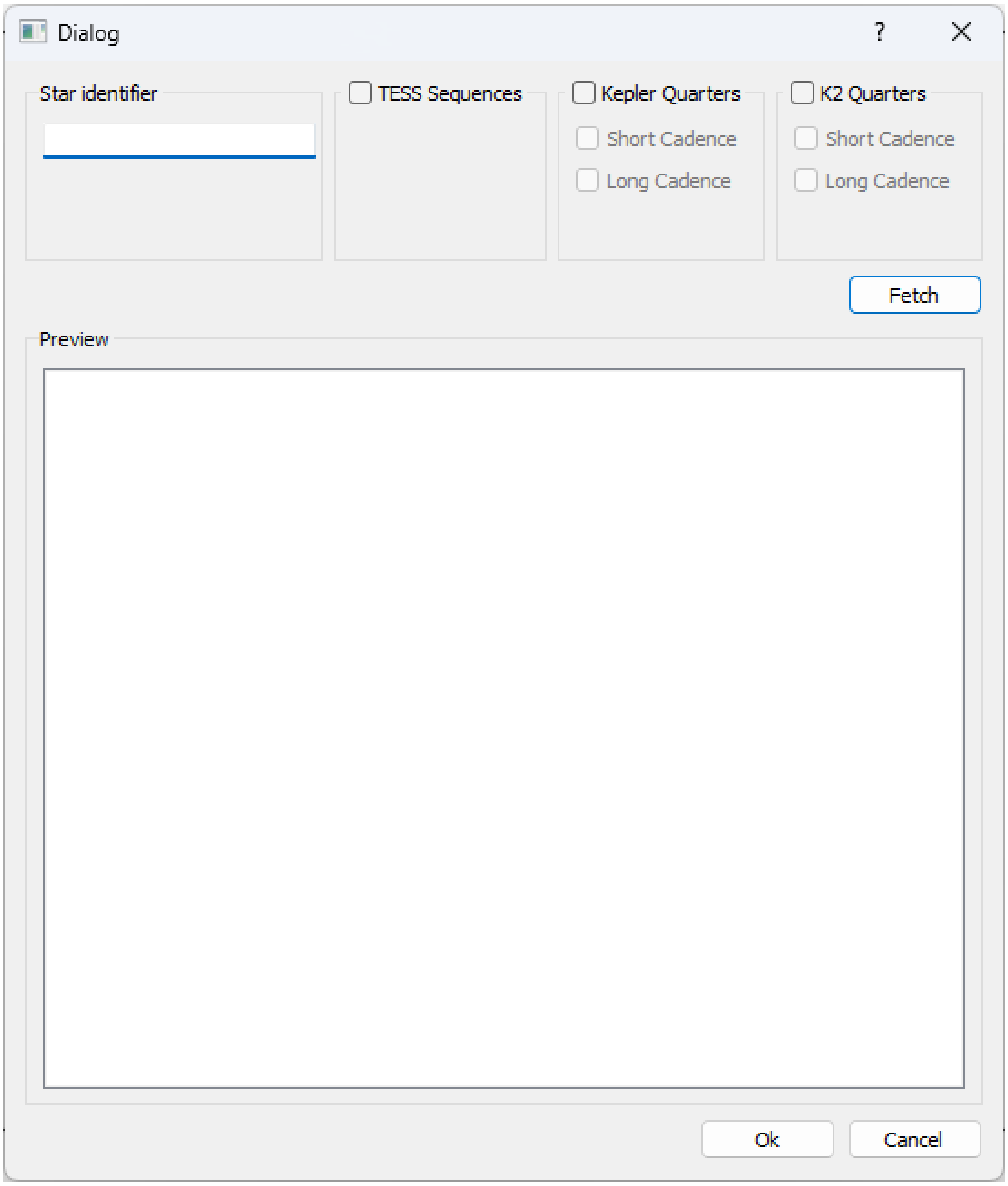

Fig. 2.1.: GUI window for downloading new fit files with astroquery designed using the Qt5 designer shipped with PyQt5 (Riverbank Computing Limited (2025)). The star identifier field supports one or more (separated by a semicolon) identifiers. There are checkboxes to select TESS, Kepler (long and/or short cadence) and K2 (long and/or short cadence) data. The preview field shows metadata (Identifier, TESS quarter or Kepler/K2 target table ID) to check the data which was found and which can be downloaded. The "Ok" button then proceeds to download the data and hands information back to the main GUI.

and sector/target table id are saved into a local database using SQLite3 (SQLite Development Team (2025)).

2.2 Data display and manipulation

Afterwards the list of stars seen in figure 2.2 will be refreshed. It shows the via Simbad determined main identifier alphabetically sorted.
When one of the stars in the list is selected, the program will show the additional saved informations. This includes all known IDs (in the Alt. IDs list), the spectral type, its rotational velocity and its distance. Additionally a fit type for the folded lightcurves which are described in section 3.2. The default for this is "sine". The list to the right of the information section shows the available fit files. The formating for the list entries is "TESS - <sequence>" and "Kepler/K2 - <target table id>". The combine button allows to show multiple fit files at once if multiple are selected. Select one or combining multiple fit files, enables the plot options.
The main plot options allow the user to change the type of flux thats plotted. This is either "SAP_FLUX" (simple aperture photometry) or "PDCSAP_FLUX" (presearch data conditioning simple aperture photometry) (Lightkurve Collaboration et al. (2018)). The PDCSAP_FLUX has parts of its data removed depending on the quality flags (e.g. indicating systematic errors like an attitude tweak or a cosmic ray (Twicken et al. (2020), Thompson et al. (2016))) as well as corrected long-term brightness changes (Lightkurve Collaboration et al. (2018)). An example of a PDCSAP_FLUX is shown in figure 2.2.
The lightkurve python package also supports normalizing (to unscaled, percent, parts per thousands (ppt) or parts per million (ppm)) which can be seen in figure 2.4. Flattened lightcurves (see figure 2.5 as an example for $BD - 08\ 995$) is used to identify flares. The "remove outliers", "remove nans/infs" and "bin" features are exposed in the GUI, but are not actively used in this thesis.
The checkboxes to flatten the lightcurve (figure 2.5), fold the lighhtcurve (figure 2.6) and showing the periodogram (figures 2.7 and 2.8) are exclusive of each other. Only one can be used at a time.

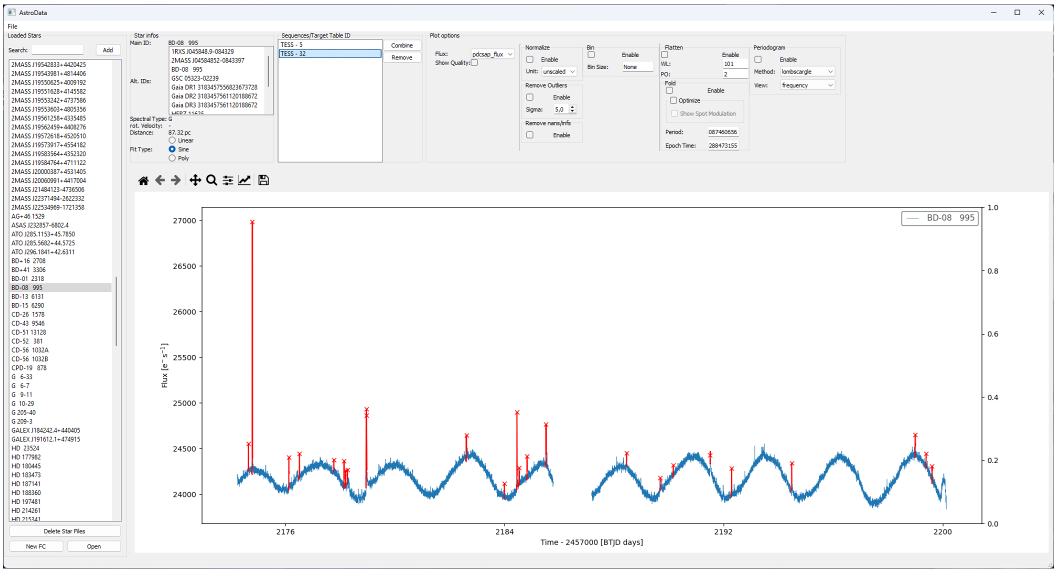

Fig. 2.2.: Main GUI window. This window was designed with the Qt5 designer shipped with PyQz5 (Riverbank Computing Limited (2025)). It shows a list of all available stars with their main identifier (taken from SIMBAD (Wenger et al. (2000))) sorted alphabetically. The "Star infos" box contains additional information on the star gathered from SIMBAD. There is a list of alternative IDs, the spectral type, the roational velocity, and the distance. It also shows the prefered fit type for folding lightcurves. On the right of the information box is a list of all available lightcurves, with an option to combine multiple to plot at once. To the right of the list of available lightcurves are multiple different plot options, which utilize the different capabilities of the lightkurve python package (Lightkurve Collaboration et al. (2018)). The values for "Period" and "Epoch Time" are automatically calculated and used as default for the selected lightcurve. In this image the TESS Sector 32 lightcurve of $BD - 08\ 995$ is shown. The red crosses show the peaks of the found flares, while the red overall over the lightcurve indicates the duration of the flare.

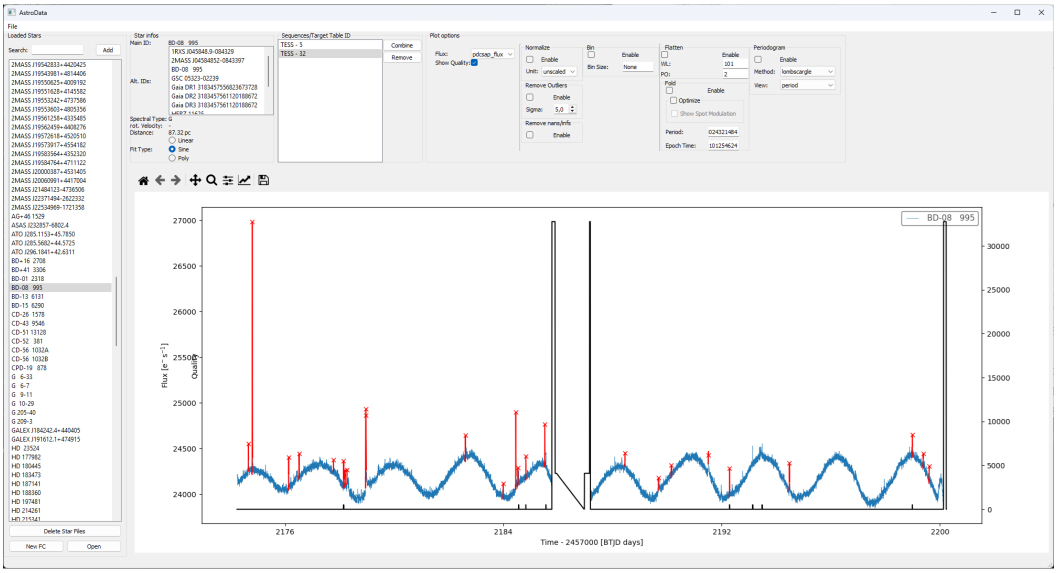

Fig. 2.3.: Main GUI window. Same as in figure 2.2, with the difference that the data quality flag is also shown.

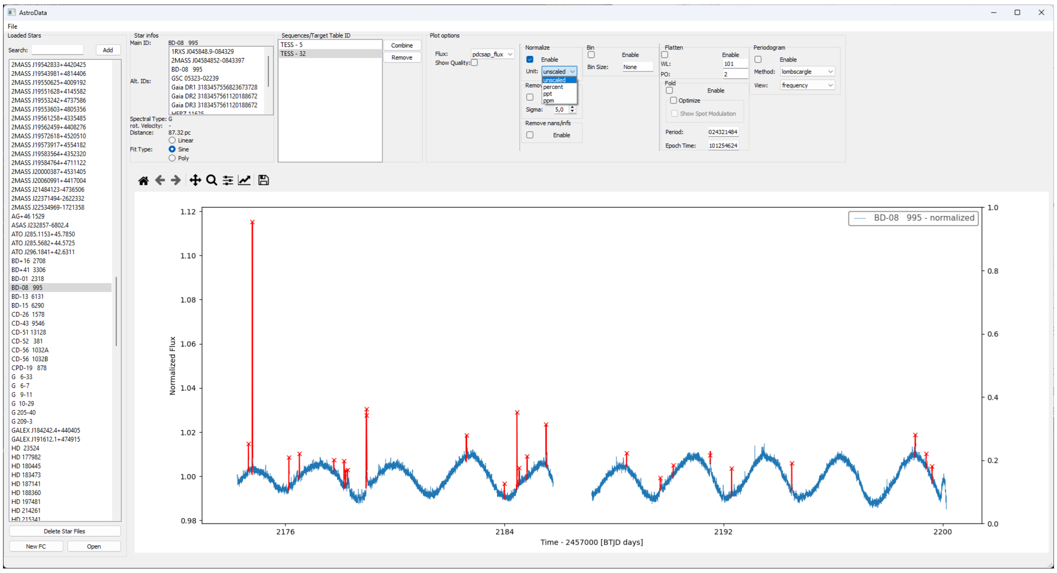

Fig. 2.4.: Main GUI window. Same as in figure 2.2, with the difference that the lightcurve was normalized. It also shows all possible normalize options the lightkurve python package (Lightkurve Collaboration et al. (2018)) supports.

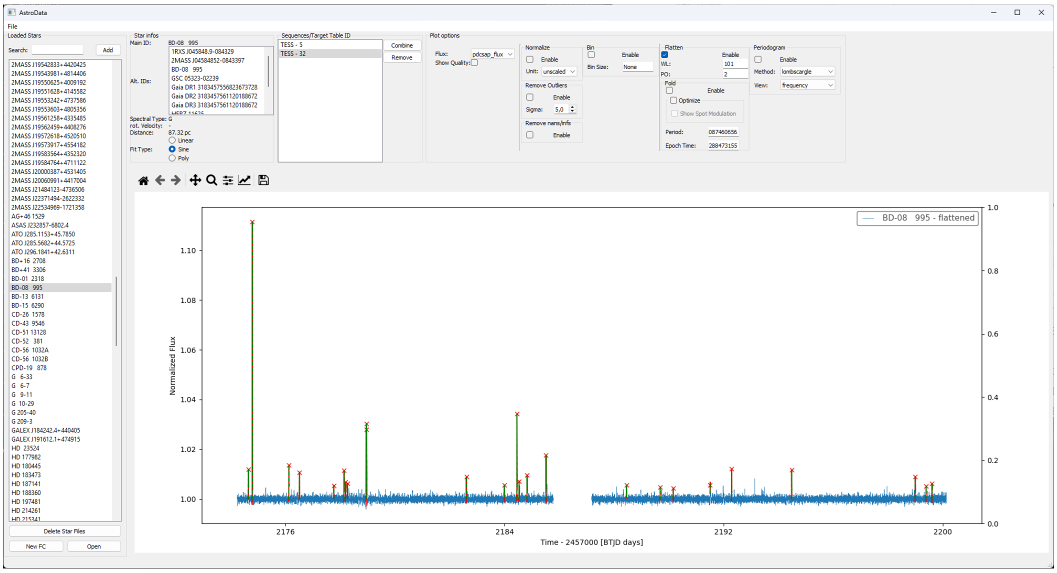

Fig. 2.5.: Main GUI window. Showing the same lightcurve as figure 2.2, with the difference that it is now flattened. The green line shows a fit of the flare. This is described in chapter 3.2.

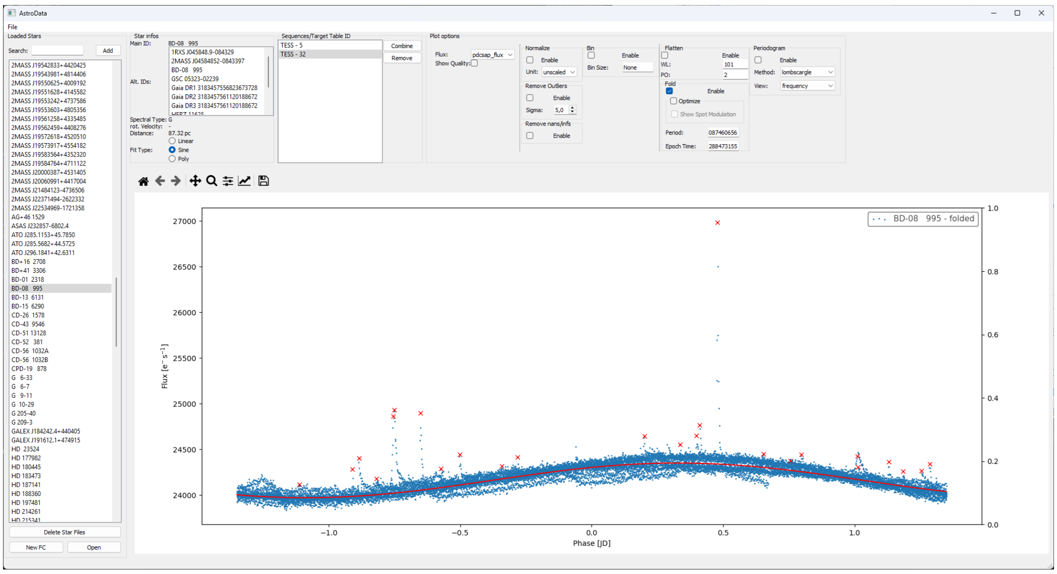

Fig. 2.6.: Main GUI window. Showing the same lightcurve as figure 2.2, with the difference that it is now folded with an period of 2.697 days. Additionally vertical lines are shown which indicate the region around the minima and maxima of the folded lightcurve respectively.

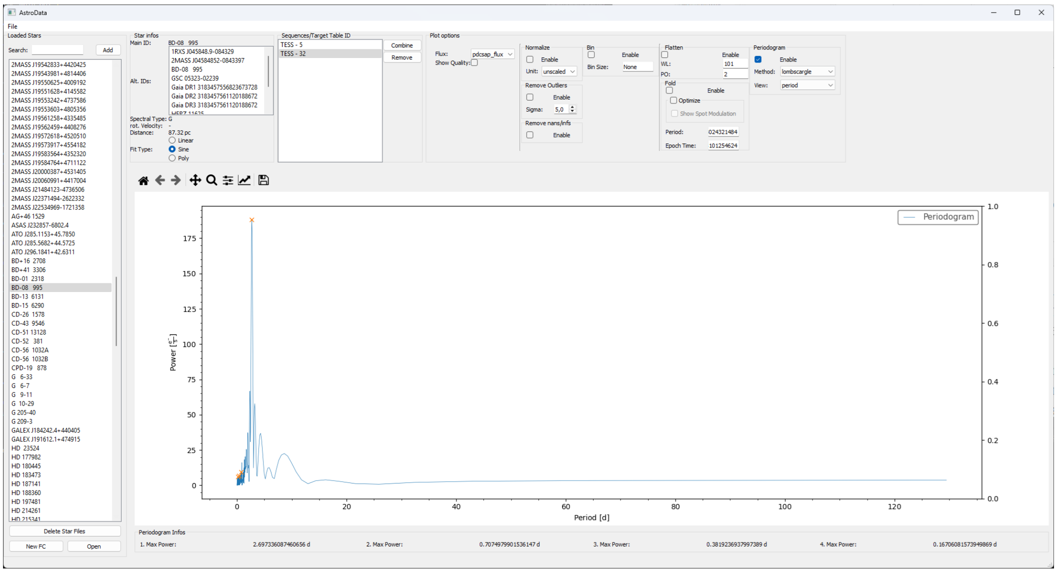

Fig. 2.7.: Main GUI window. Showing the periodogram of the lightcurve in figure 2.2 using the lombscargle algorithm. Furthermore it shows the four highest peaks (which are atleast 100 datapoints separated). The method is explained in chapter 3.2.

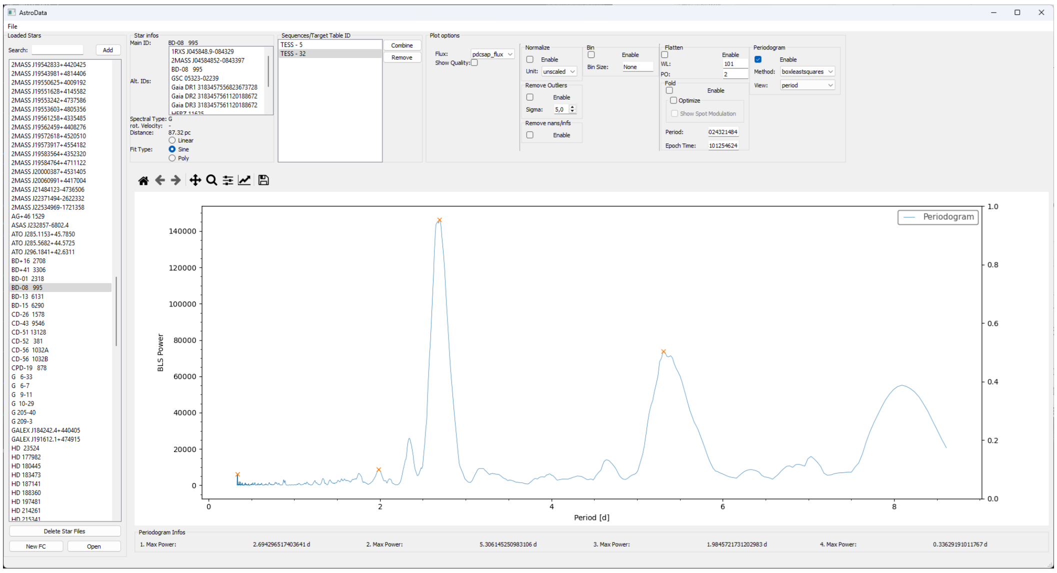

Fig. 2.8.: Main GUI window. Showing the periodogram of the lightcurve in figure 2.2 using the box least square algorithm. Similarly to figure 2.7 the four highest peaks are marked with a red "x".

2.3 Data processing

Pressing the button "New FC" will start the processing of all fits files in the current loaded database. It will sequentially go through all files and apply the flare detection algorithms to the lightcurve, as well as generate the periodogram and optimized folded lightcurves. This is done for the PDCSAP_FLUX. Additionally plots for each individual lightcurve and processing step are generated. The included data includes:

- Flares (peak, timestamp, datapoint index in the lightcurve, TESS/Kepler data quality flags)
- Number of flares
- Fits for the flares (fit, timestamps, indices in the lightcurve, TESS/Kepler data quality flags)
- Uninterrupted timespans in the data
- Total length of timespans in seconds
- Rotational period
- Spot modulation period
- Folded lightcurve phase range
- Folded lightcurve flare positions (phase, peak)
- Period which was used to fold the lightcurve
- Additional boundaries around minima and maxima

And in the case the period and spot modulation of the star differs, it will seperately safe the folded lightcurves and related data for the stars period as well.

After this process is done, a new window will open. It allows to show multiple different statistics like flares per file, flares per star (total, or normalized to per 7 day period) or mean periods for each star. This window can be seen in figure **??**. The data can then be saved using the pandas (team (2020b)) "to_pickle" functions and also loaded again using the "read_pickle" function.

Table 3.1.: Training sample of false-positive planet candidates for the clustering algorithm.

Star's identifier	T_{eff} [K]	Lum [L/L$_\odot$]	Luminosity cluster	Reference
π Her	4170	1320	High	Hatzes and Cochran (1999)
μ UMa	3899	1150	High	Lee et al. (2016)
HD 18438	3871	830	High	Delgado Mena et al. (2018)
γ Dra (Eltanin)	3990	510	High	Hatzes et al. (2018)
α Tau (Aldebaran)	4055	440	High	Hatzes et al. (2015)
θ^1 Tau	5000	70	Low	Beck et al. (2015)
NGC2423 No.3	4592	65	Low	Delgado Mena et al. (2018)
γ Psc	4909	60	Low	Beck et al. (2015)
β Gem (Pollux)	4865	40	Low	Delgado Mena et al. (2018)
IC4651 No.9122	4720	35	Low	Delgado Mena et al. (2018)
γ Cep A	4900	10	Low	Hatzes and Cochran (1999)

Notes. The star's identifier is given. For the most prominent stars, the name of the star is amended in brackets. The next columns report on the effective temperature and the luminosity of the star in units of the solar luminosity L$_\odot$. The typical uncertainty of the reported temperature and luminosity are 150K and ~10%, respectively. The top and bottom panel report classification of the clustering. The cluster name refers to the position in the red-giant phase. The literature references are provided in the last column. (Table taken from Elisabeth Höldrich bachelor thesis, 2020)

3 Data and Methods

In this chapter the selection criteria for the data is explained is section 3.1. Furthermore a detailed description of the algorithm is given in section 3.2.

3.1 Data selection

3.2 Data reduction algorithms

3.2.1 This is a subsection

3.3 Example of a code snippet

Listing 3.1: Example for setting the tidal mechanisms in the *star_star* inlist.

```
1 &binary_controls
2           do_tidal_circ = .true.
3           circ_type_1 = 'Hut_conv'
4           circ_type_2 = 'Hut_conv'
5
6           do_tidal_sync = .false.
7           sync_type_1 = 'Hut_conv'
8           sync_type_2 = 'Hut_conv'
```

Notes. A part of *&binary_controls* environment in the *star_inlist* is shown. The true/false-statements in line 2 and 6 determine if the models defined below takes into account the defined mechanism. The keywords for defining the formalistic description for circularization and synchronization mechanism are defined in lines 2-4 and 6-8, respectively. The number at the end of the keyword indicates which formalism is set for the primary (1) and secondary (2) stellar component.

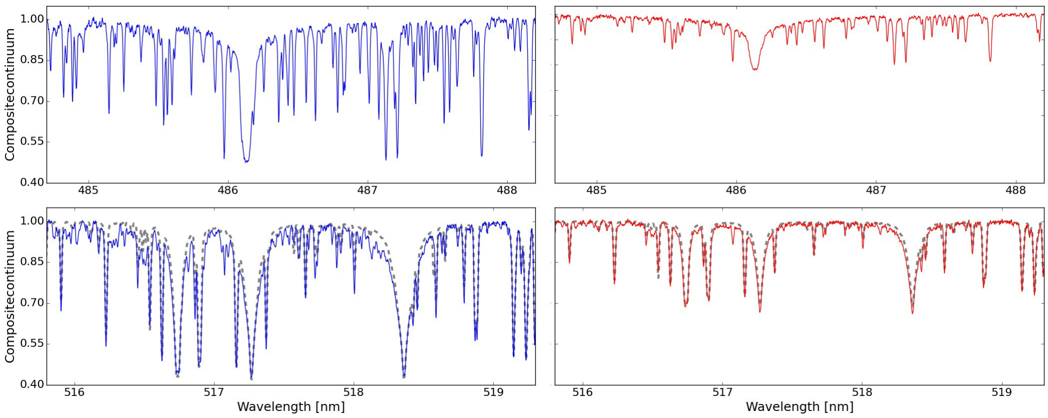

Fig. 3.1.: Disentangled spectra of KIC 9163796. The spectra of the primary in blue and secondary in red are shown in the left and right spectrum, respectively. Top panel: the region around the Hβline, while bottom panel: magnesium triplet at 518 nm, normalised to the continuum flux of the composite spectrum. The synthetic model of the best fit of the determination of fundamental parameters and metallicity is shown as dashed grey line is shown depicted in the region of the Mg triplet. (Graphic taken from Beck et al., 2018)

Table 3.2.: Seismic and fundamental parameters for 14 oscillating red giant heartbeat stars, ordered by descending orbital period.

Star KIC	ν_{max} [μHz]	$\Delta\nu$ [μHz]	$\Delta\Pi_1$ [sec]	δf_{max} [nHz]	Evol. Phase	R [$R_\odot$]	M [$M_\odot$]	$\log g$ [dex]	L [$L_\odot$]	T_{eff} [K]	P_{orbit} [d]	A [ppt]	$\lvert\Delta RV\rvert$ [km s^{-1}]
9151763	13.8±0.2	1.98±0.01	–	–	RGB?	17.6±0.4	1.19±0.08	2.01	96±16	4290	437.5	+7.1	32.2
7431665	54.0±0.7	5.46±0.02	~67	–	RGB	9.4±0.1	1.39±0.05	2.62	35±2	4580	281.4	-3.0	[37.8]
5039392	6.2±0.1	1.13±0.01	–	–	RGB	24.0±0.7	0.98±0.07	1.67	157±24	4110	236.7	-6.0	42.3
9540226*	27.4±0.4	3.18±0.01	–	–	RGB	14.1±0.3	1.6±0.1	2.37	81±13	4600	175.4	-7	45.3
8210370	44.1±0.8	4.69±0.02	–	–	RGB?	10.5±0.2	1.40±0.08	2.54	44±4	4585	153.5	-5.3	22.1
11044668	50.2±0.2	5.65±0.01	~60	83(?)	RGB	8.18±0.09	0.99±0.03	2.59	26±3	4565	139.5	-3.8	[43.0]
10614012*	70.2±0.9	6.54±0.02	–	–	RGB	8.6±0.2	1.49±0.08	2.74	33±4	4715	132.1	-4.7	49.3
9163796	153.2±0.7	13.53±0.04	–	–	RGB	4.46±0.03	0.89±0.01	3.09	12±1	4820	121.3	±0.5	70.1
2444348	30.5±0.3	3.26±0.01	–	–	RGB	14.9±0.3	1.94±0.11	2.38	86±14	4565	103.5	-1.7	7.7
5006817	145.9±0.5	11.64±0.01	78	450	RGB	5.84±0.09	1.49±0.06	3.08	19±3	5000	94.8	-1.7	23.5
8803882	347±3	22.6±0.4	–	500(?)	RGB	3.68±0.1	1.4±0.1	3.45	8±1	5043	89.7	+0.5	[1.9]
8144355	179±2	13.95±0.04	~78	210(?)	RGB	4.90±0.09	1.26±0.08	3.16	12±2	4875	80.6	+2.1	18.9
9408183	164.8±0.2	13.29±0.02	~93	450	RGB	5.02±0.07	1.23±0.05	3.12	13±1	4900	49.7	+1.5	64.4
2720096	110.1±0.7	9.17±0.01	–	–	RGB	6.98±0.08	1.54±0.06	2.95	23±2	4812	26.7	+1.0	4.0
8095275	69.3±0.3	6.81±0.01	–	–	RGB	7.78±0.08	1.21±0.05	2.74	25±3	4622	23.0	-6.0	20.6

Notes. The star's identifier in the *Kepler* Input Catalogue (KIC) is given. Eclipsing systems are marked with an asterisk. The columns ν_{max} and $\Delta\nu$ report the frequency of the oscillation power excess and the large frequency separation between radial modes for a given star. $\Delta\Pi_1$ quantifies the true period spacing of dipole modes. The maximum value of the detected rotational splitting δf is listed. The evolutionary phase RGB describes H-shell burning red giant. Ambiguous values are marked with '?'. The columns R, M, L, and $\log g$ report the stellar radius, mass, luminosity, effective temperature and surface gravity from scaling relations, respectively. T_{eff} was adopted from the KIC. The uncertainties of $\log g$ are on the order of 0.01 dex and for the temperature typically smaller than 150 K. P_{orbit} gives the orbital period from photometry. The column A lists the maximum amplitude of the heartbeat in a rebinned phase diagram. The error estimate for P_{orbit} and A from the PDM is not reliable due to the remaining contamination of the solar-like oscillations and therefore not given. $\lvert\Delta RV\rvert$ reports the maximum difference in radial velocity. Squared brackets mark systems for which the orbital parameters could not yet be determined from radial velocities. (Table taken from Beck et al., 2014)

4 Results

This chapter includes the main results of this study. The data for the plots were generated using the "New FC" Button from the main GUI described in section 2.3. The results are first split into the overall results for the different spectral types M, K, G, and F as well as combined results over all analyzed spectral types. Furthermore there is a selection of individual star results. The results also only contain the data of folded lightcurves which could be fitted with a sine function and less than 30 iterations of the fold optimization. The data which uses polynomial fits or both sine and polynomial fits is available at google drive.

4.1 M dwarfs

This section shows the results for all M dwarfs in this study.
Figures 4.1 and 4.2 show histograms, with 10 and 30 bins respectively, of the amount of flares during the normalized phase. Looking at figure 4.1 there is a rather even distribution across the whole phase, except at 0.5π. There is a clear dip in the amount of flares happening visible.
Looking at the same data, just with 30 bins (figure 4.2), the same dip is visible. Additionally there also seem to be a dip at phase 1.5π.

Filtering the data by the minimal flare peak (see figures 4.3 to 4.6), makes the trend of figure 4.2 clearer. There are increasinly more flares in the minima (more/bigger star spots) and maxima (less/smaller star spots) compared to the transition.

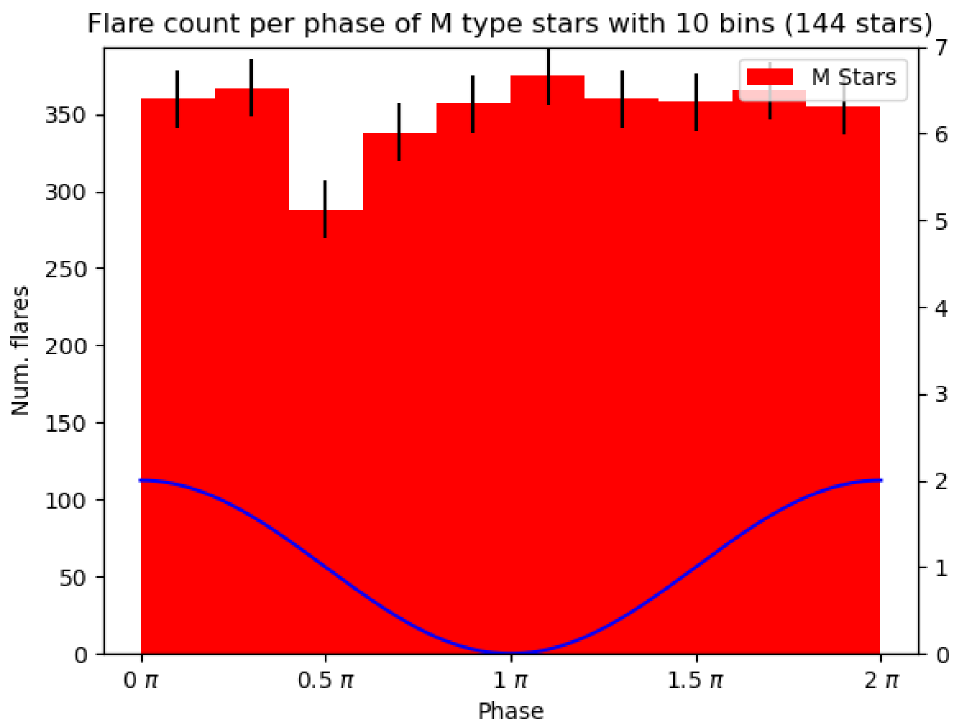

Fig. 4.1.: Histogram of all M dwarfs with 10 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

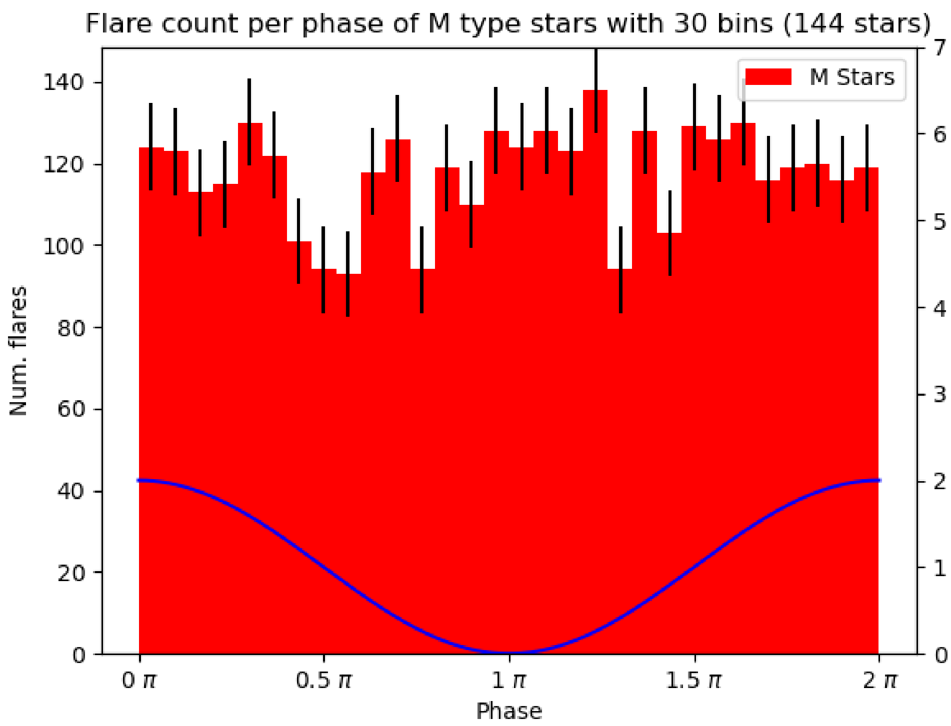

Fig. 4.2.: Histogram of all M dwarfs with 30 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

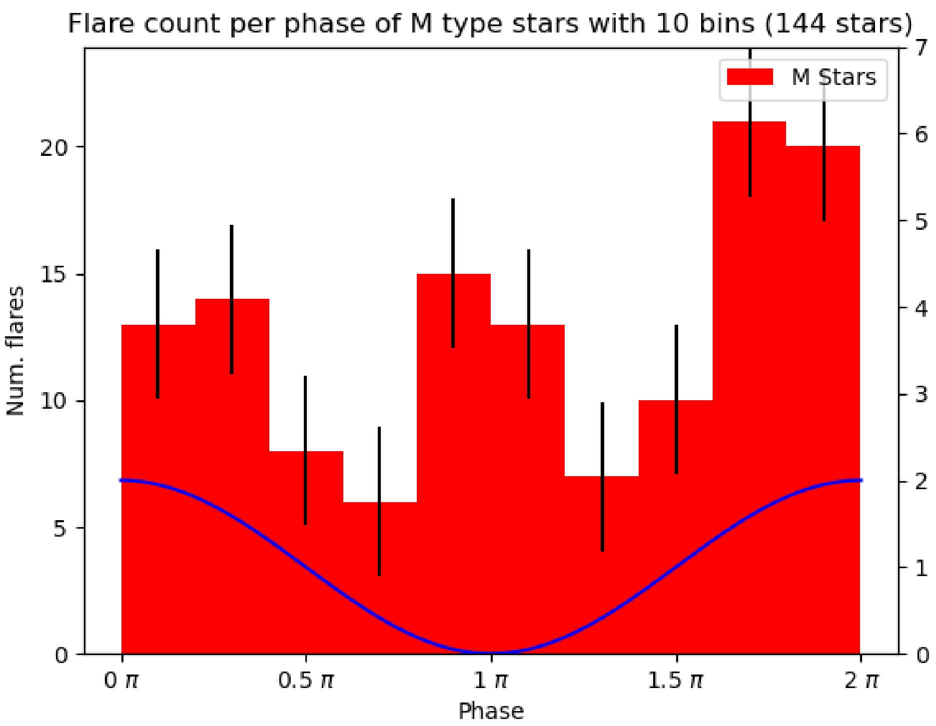

Fig. 4.3.: Histogram of all M dwarfs with 10 bins across the phase showing the number of flares with normalized peak above 1.25 in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

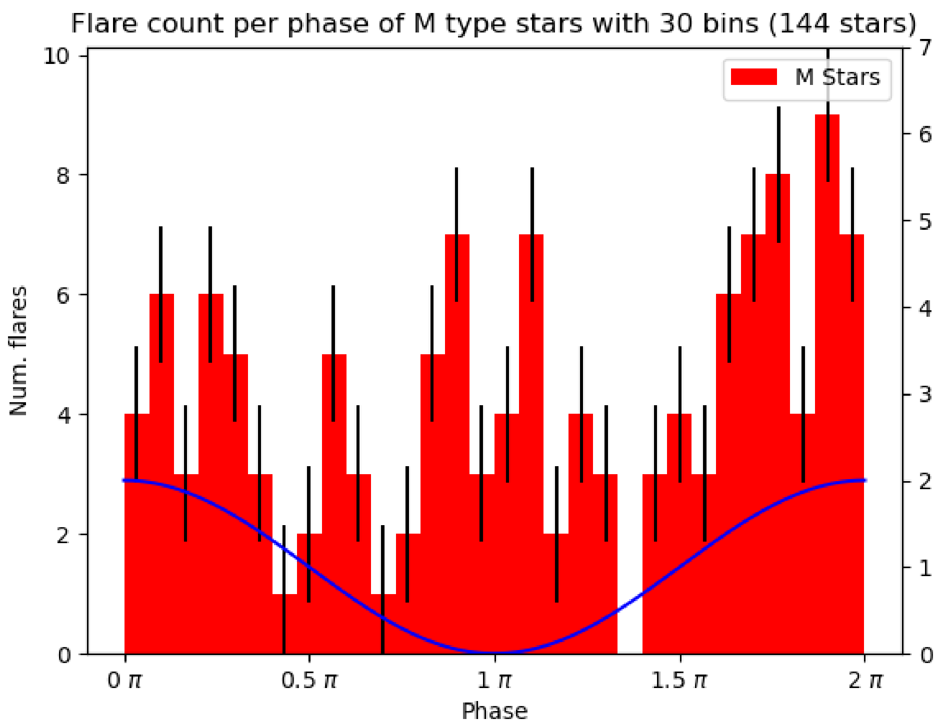

Fig. 4.4.: Histogram of all M dwarfs with 30 bins across the phase showing the number of flares with normalized peak above 1.25 in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

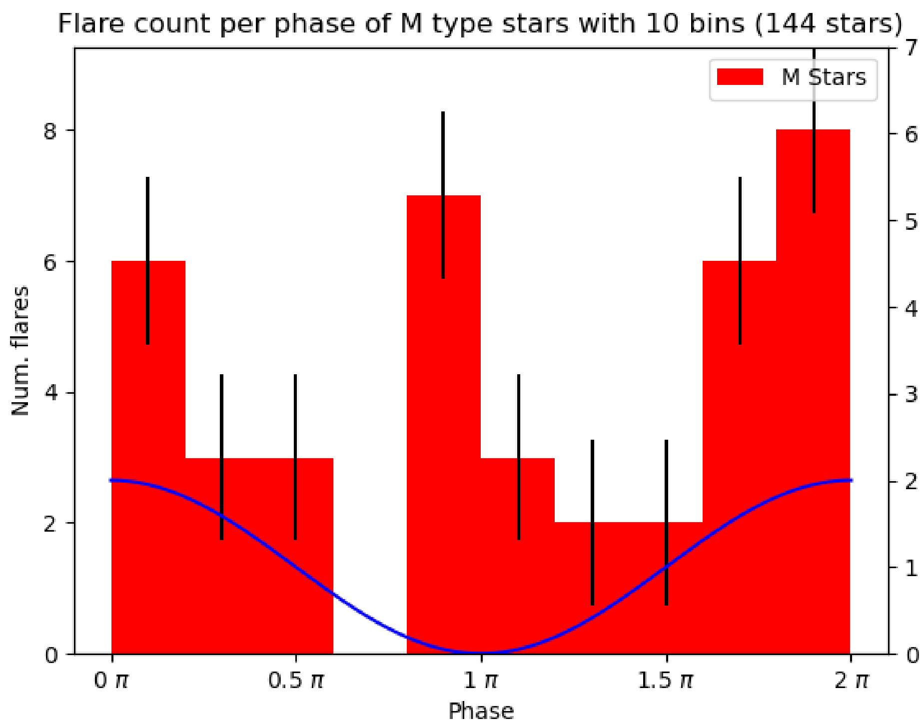

Fig. 4.5.: Histogram of all M dwarfs with 10 bins across the phase showing the number of flares with normalized peak above 1.5 in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

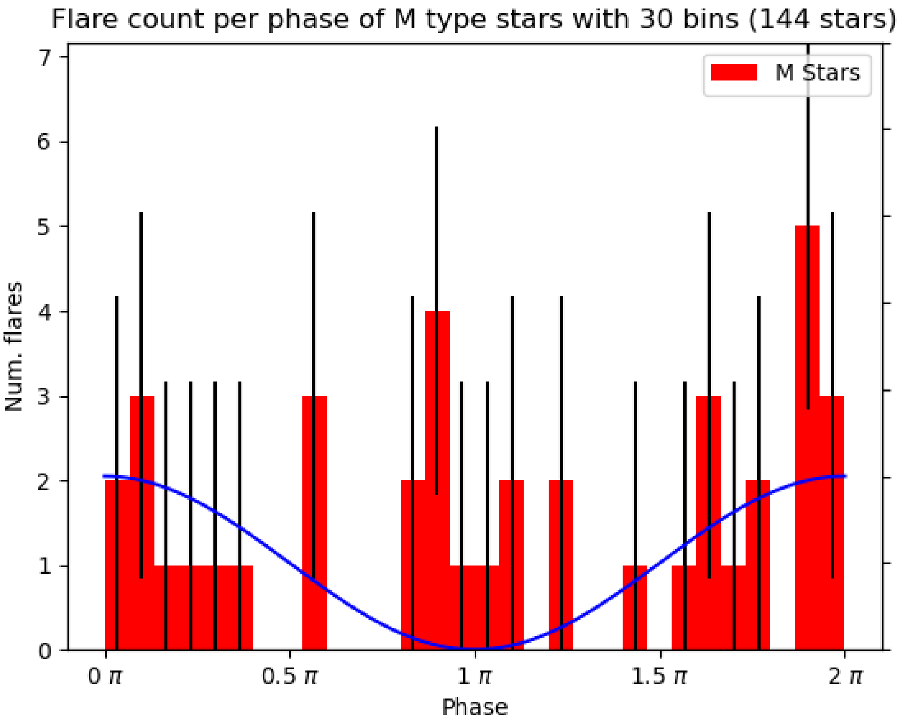

Fig. 4.6.: Histogram of all M dwarfs with 30 bins across the phase showing the number of flares with normalized peak above 1.5 in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

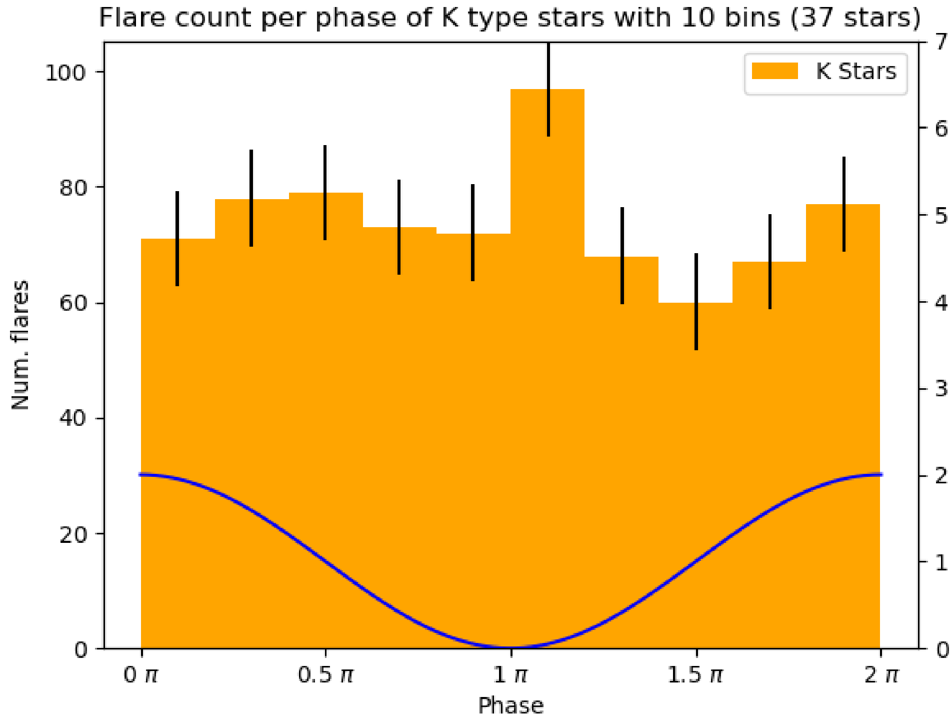

Fig. 4.7.: Histogram of all K dwarfs with 10 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

4.2 K dwarfs

This section shows the results for all K dwarfs in this study.
Figure 4.7 shows the amount of flares per phase with 10 bins of all K type dwarfs in used in this study. Overall the distribution is even, with a slight increase in flares when going from the maximum to the minimum of the lightcurve, and a slight decrease when going from minimum to maximum. There is also a peak at around 1π. This peak is dominated by $V * V471Tau$. The plots for this are visible in section 4.6.
Looking at the same dataset with 30 bins for the histogram (figure 4.8), the peak in the center is still visible. Additionally there appear more peaks at phase $> 1.3\pi$, while the amount of flares between phase 0π and 1π shows a light trend to more flares, with a dip right before and after the big peak which was also visible in figure 4.7 with 10 bins.

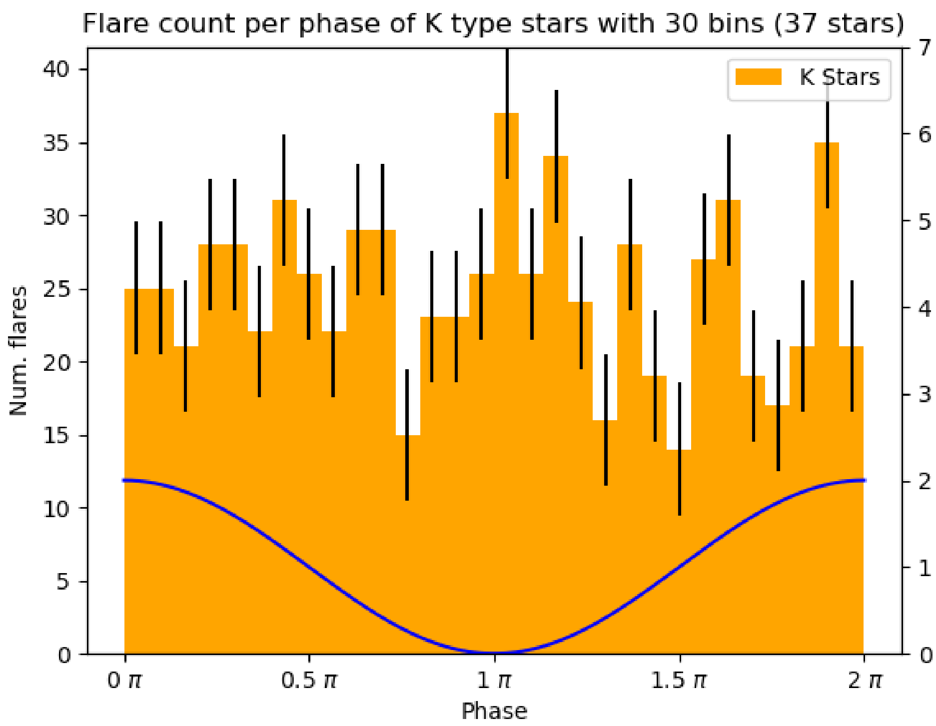

Fig. 4.8.: Histogram of all K dwarfs with 30 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

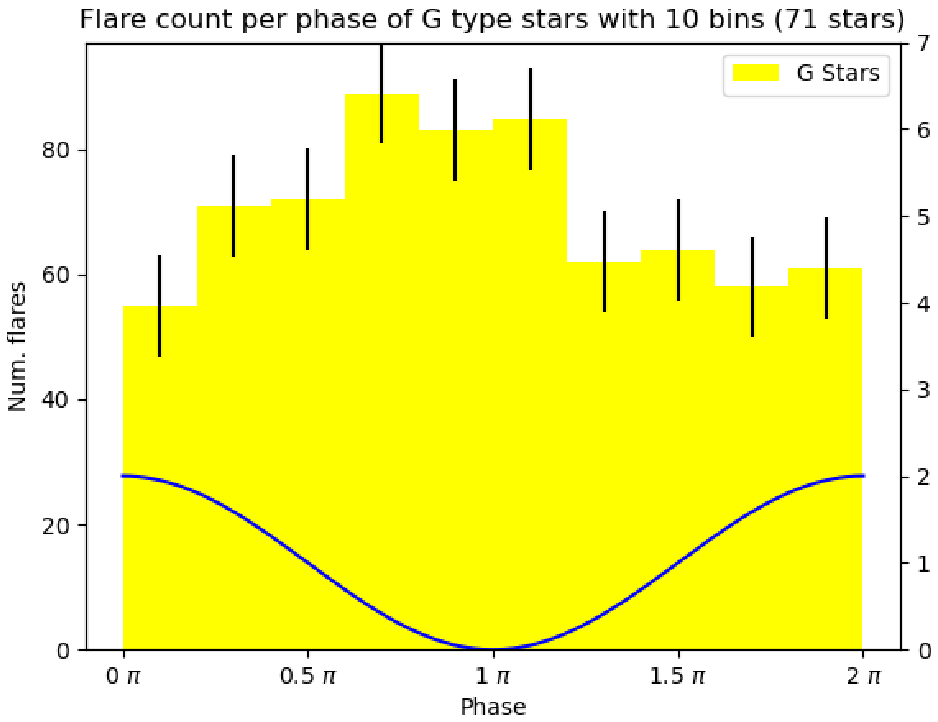

Fig. 4.9.: Histogram of all G dwarfs with 10 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

4.3 G dwarfs

This section shows the results for all G dwarfs in this study.
The first histogram over all data of G type dwarfs with 10 bins in figure 4.9 shows a rise of occuring flares in the lightcurve minima compared to the maxima. The rise in flare occurances from maxima to minima (phase 0π to 1π) seems to be gradual, while there is a steep fall off afterwards.
Due to the lower number of detected flares on G type stars, the error bars in figure 4.10 are rather large. Nontheless the same peak as in figure 4.9 can be seen. It is even split into 2 peaks which are rather close together at around phase 0.6π and 1π.

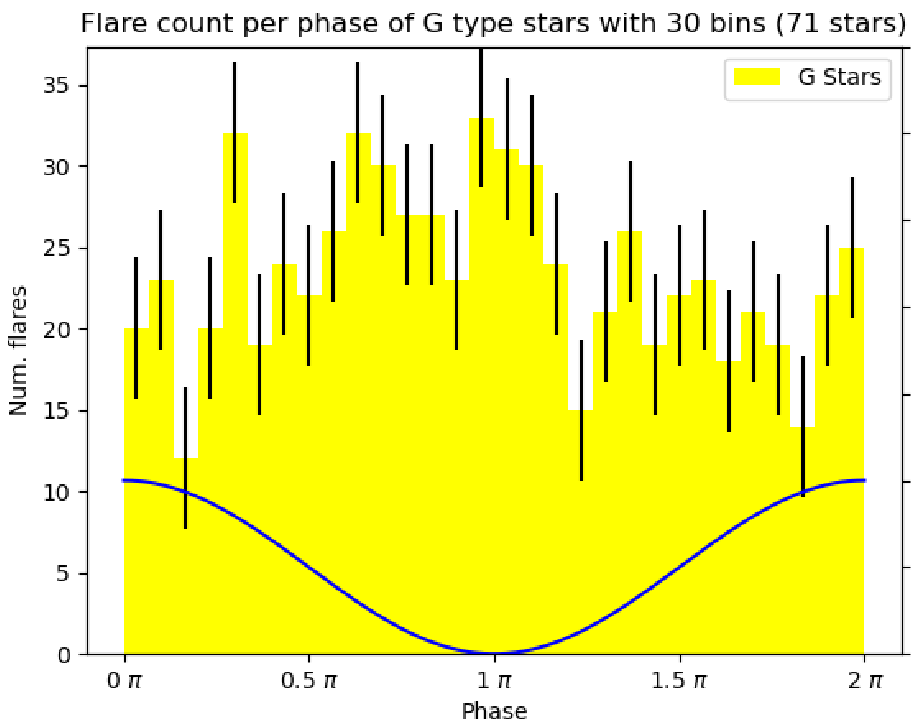

Fig. 4.10.: Histogram of all G dwarfs with 30 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

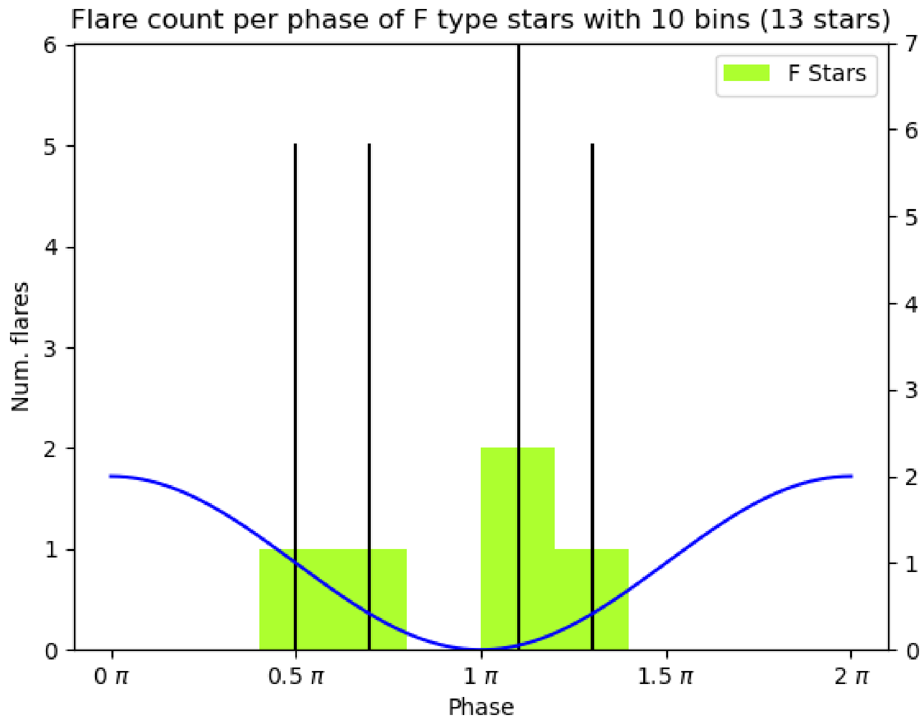

Fig. 4.11.: Histogram of all F dwarfs with 10 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

4.4 F dwarfs

This section shows the results for all F dwarfs in this study.
Due to the low number of F type stars in this study, and the difficulty to detect flares on them, the detected number of flares in figures 4.11 and 4.12 is very low which causes the errorbars of the histogram to grow very large. Nontheless all detected flares were around the minimum of the lightcurves.

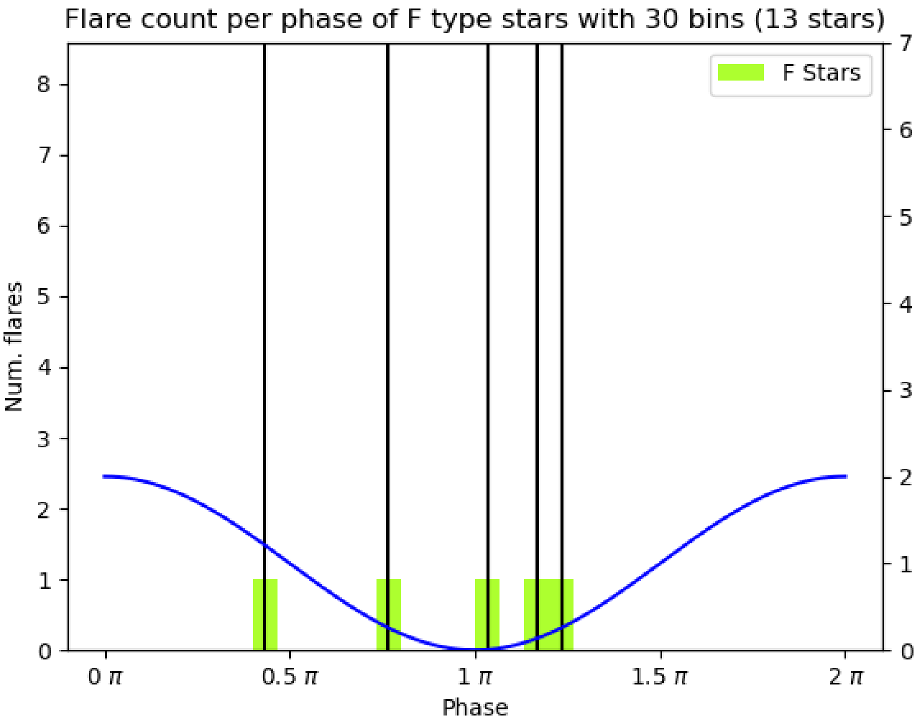

Fig. 4.12.: Histogram of all F dwarfs with 30 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

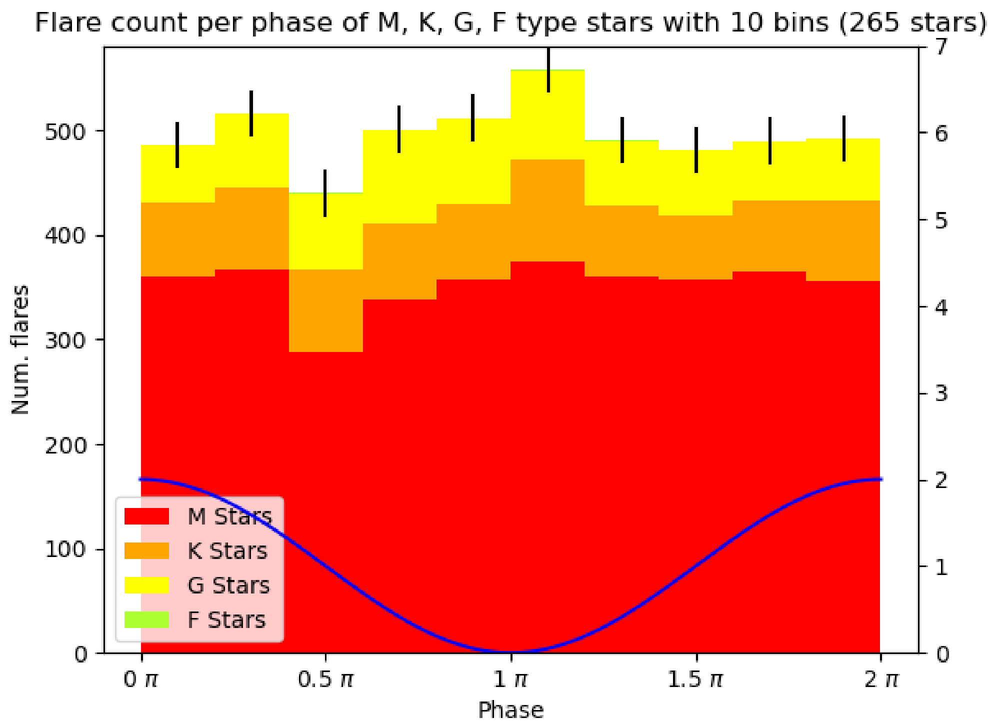

Fig. 4.13.: Histogram of all dwarfs (spectral types M, K, G and F) with 10 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

4.5 Combined results

The results for all stars in the study are shown in this chapter. The histograms in figure 4.13 and 4.14 are stacked histograms. The flare amount of the individual stars are per bin are stacked on top of each other resulting in the final value. The dip which was present in the histogram for the M type stars (see figure 4.1) propagates and the dip is also visible in figure 4.13. The peak at phase 1π is also a result of propagation, but from the K and G type star data.
Looking at the same data with 30 bins over the phase in figure 4.14, the propagation of the variation in the data of the M type stars is clearly visible. Additionally the peaks from the data of K (figure 4.8) and G (figure 4.10) type stars help to make it overall clearer to see. While there is a slight peak at around phase 1π, there are also smaller, especially less wide peaks at around phases 0.4π, 0.7π and 1.5π. The dips in the data of the M type stars also propagate in this plot.

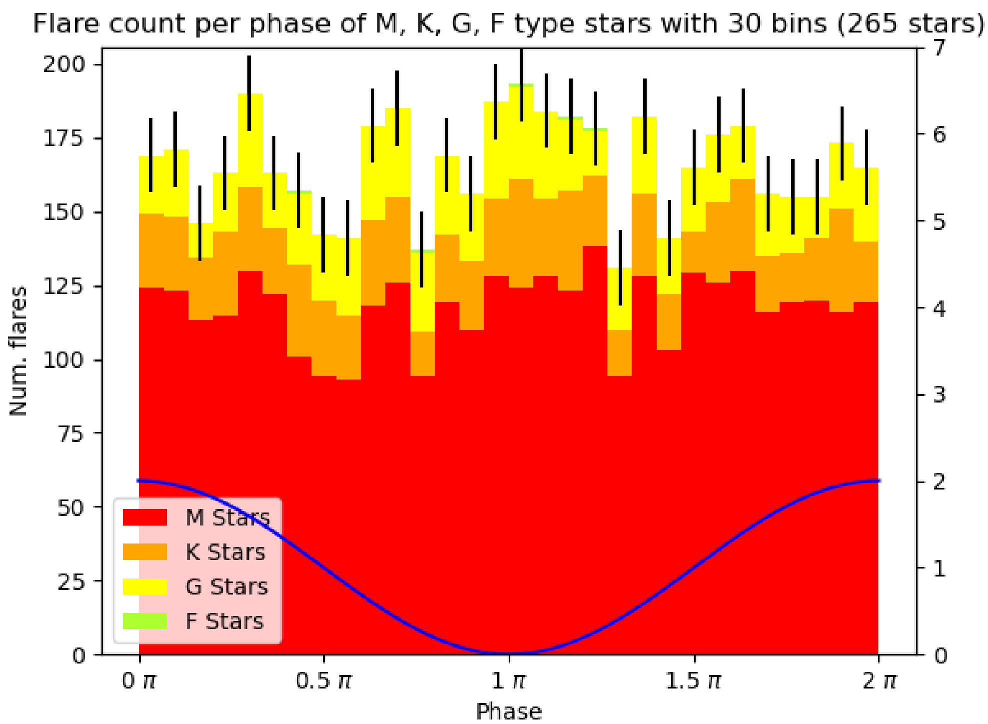

Fig. 4.14.: Histogram of all dwarfs (spectral types M, K, G and F) with 30 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idialized phase, with the minimum at phase 1π.

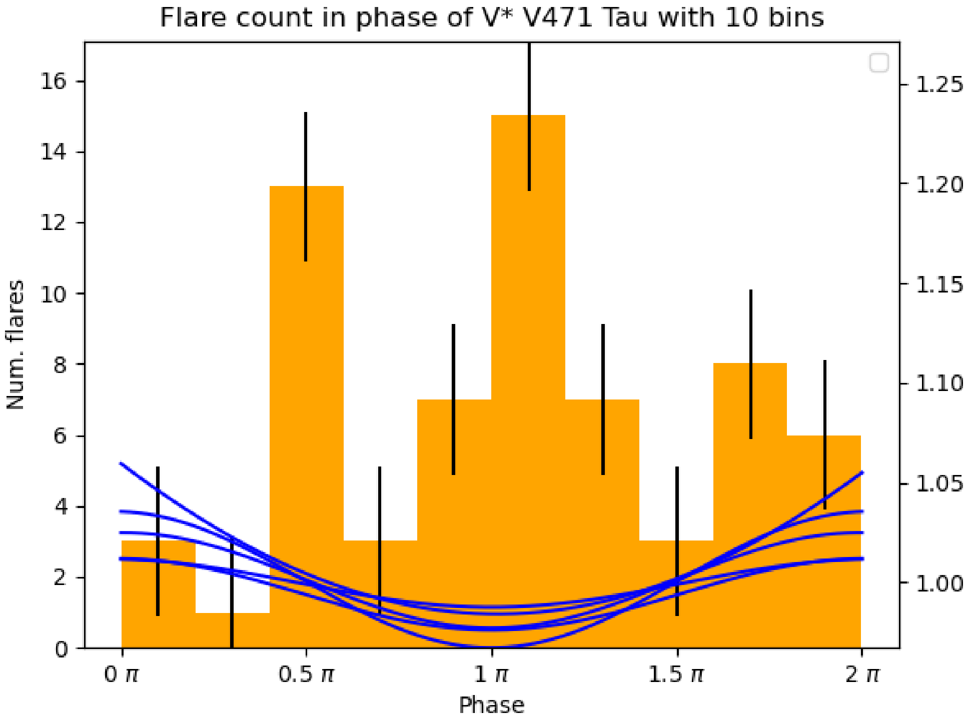

Fig. 4.15.: Histogram of V471 Tau with 10 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the minimum at phase 1π.

4.6 Individual stars

This section contains a selection of results for individual stars. The results for this section were selected because either they match exactly what this study was looking for or because the opposite is the case.

4.6.1 V* V471 Tau

V471 Tau is a binary system consiting of a K2 type dwarf and a white dwarf (<ref>). The K2 dwarf is also tidally locked to its companion, with a large spot facing the white dwarf (ref).
In figure 4.15 there is a clear peak in flare count visible in the bin starting at phase 1π. There is also another peak at phase 0.5π. The histogram looks similar if the bin size is increased to 30 (figure 4.16).

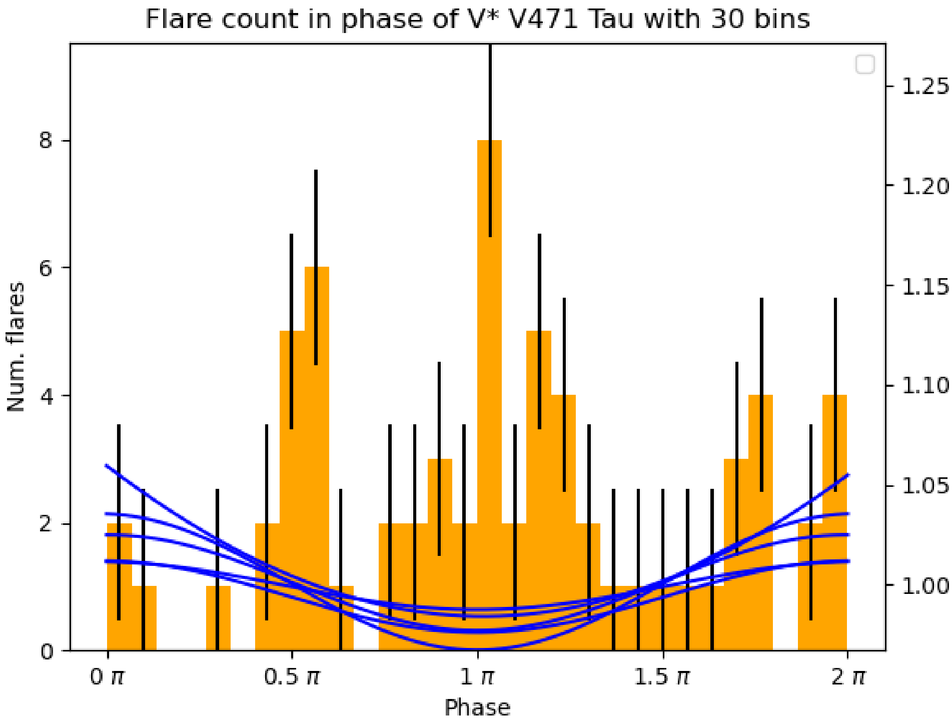

Fig. 4.16.: Histogram of V471 Tau with 30 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the minimum at phase 1π.

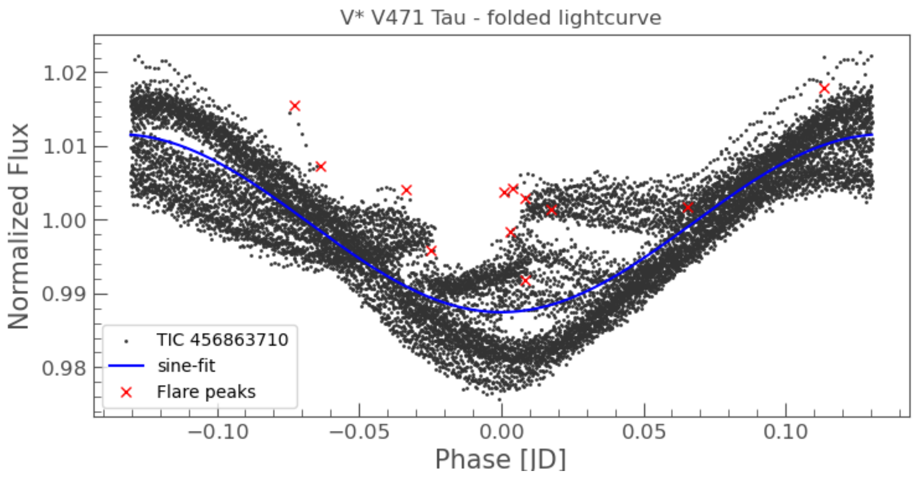

Fig. 4.17.: Folded lightcurve for V* V471 Tau and TESS Sector 42. The blue line shows the sine fit calculated. The red crosses indicate the detected flare peaks.

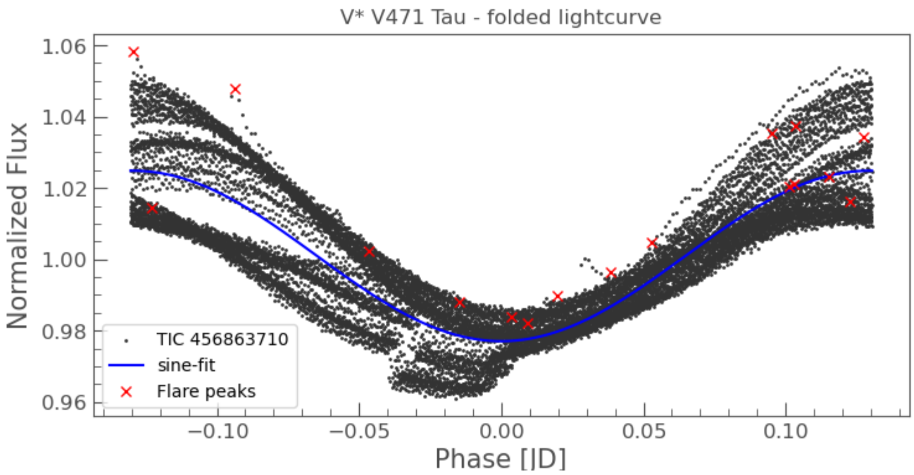

Fig. 4.18.: Folded lightcurve for V* V471 Tau and TESS Sector 43. The blue line shows the sine fit calculated. The red crosses indicate the detected flare peaks.

Looking at the folded lightcurves for this star (see figures 4.17, 4.18 and 4.19), the transit of the white dwarf (sudden dip in the folded lightcurve) is clearly visible, and always happens around phase 0.

Furthermore the distribution of flare peaks in figure 4.20 show that the largest flares happen right before, during and after phase 1π, which is the phase in which the white dwarf transit happens.

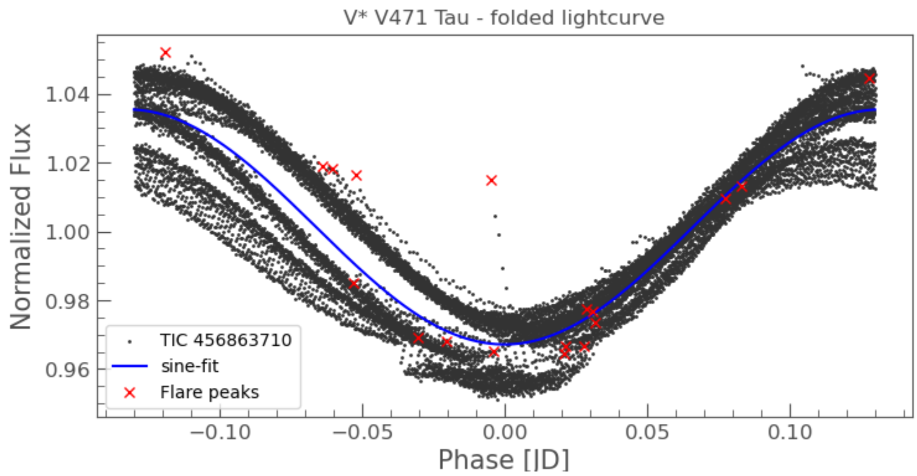

Fig. 4.19.: Folded lightcurve for V* V471 Tau and TESS Sector 44. The blue line shows the sine fit calculated. The red crosses indicate the detected flare peaks.

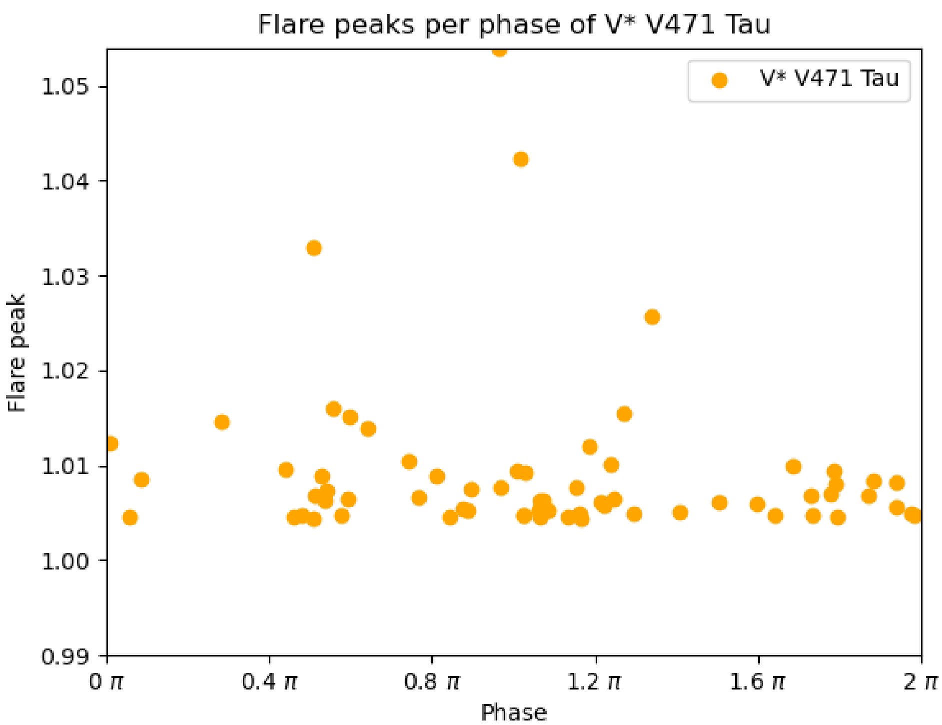

Fig. 4.20.: Distribution of flare peaks in relation to the normalized phase at which they occured. Y-Axis limited to the values of the highest peak detected.

5 Discussion

6 Conclusion and Outlook

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A

Literature values for *Kepler* systems

[This appendix has been published as Appendix C of Beck et al. (2018)].

The parameters for eclipsing binaries are taken from the dynamical solution of G16. For the list of heartbeat stars (B14), radius and mass were inferred from seismic scaling relations and corrected for the systematic mass overestimate of 15% reported by G16. Surface rotation periods were adopted from G14, B14 and B18. For four stars of B14, KIC 7431665, KIC 11044668, KIC 8803882, and KIC 7799540, no orbital parameters have yet been published.

A.1 Compilation of literature values

We refer to the cited literature for details on the applied methodology. Table A.1 contains the following parameters,

- *KIC* specifies the target identification number in the *Kepler* Input Catalog.
- *Type* indicates if a binary system is an eclipsing binary (EB), a heartbeat system (HB), or an eclipsing heartbeat system (eHB). 'NO' indicates that the star belongs to the four non-oscillating stars of G14/G16.
- P_{orbit} is the measured orbital period.
- e is the orbital eccentricity.
- ν_{max} is the peak frequency of the excess of oscillation power.
- $R/R_\odot$ is the stellar radius in solar units. Values from B14 are seismically inferred and corrected for the 5% overestimate of seismic radius. Values from G16 originate from a dynamical solution.

- $M/M_\odot$ is the stellar mass in solar units. Values from B14 are seismically inferred and corrected for the 15% overestimate of seismic mass. Values from G16 originate from a dynamical solution.

- $q = M_2/M_1$ is the mass ratio between the two stellar components in the system. '?' indicates if q has not been determined for a given system.

- $T_{\rm eff}$ is the effective temperature.

- $P_{\rm rot}$ specifies the time scale of the flux modulation, identified as the surface rotation period. The sources of the values are G14 and B18. We round all period values to the next full day.

- The dimensionless number ε_r is proportional to the inverse of the time scale of tidal circularisation (see Eq. XX). If no value of the mass ratio is specified, ε_r is calculated for $q = 0.5$.

- REF: the last column is specifying the literature references. If several papers are reporting on a given system, values of the most recent paper are cited. Previous references are given in brackets.

Table A.1.: Literature Parameters of red-giant binaries in the *Kepler* sample.

KIC	Type	P_{orb} [days]	e []	ν_{max} [μHz]	$R/R_\odot$ []	$M/M_\odot$ []	q []	T [K]	P_{rot} [days]	ε_R []	REF
2444348	HB	103.50 ± 0.01	0.48 ± 0.01	30.5 ± 0.3	14.2 ± 0.3	1.6 ± 0.1	?	4565	-	-0.53	B14
2697935	eHB	21.50 ± 0.02	0.41 ± 0.02	~ 405.6	~ 3.1	~ 1.2	?	4883	-	-0.73	B14
2720096	HB	26.70 ± 0.01	0.49 ± 0.01	110.1 ± 0.7	6.6 ± 0.1	1.3 ± 0.1	?	4812	-	0.83	B14
3955867	EB, NO	33.65685 ± 0.00007	0.019 ± 0.002	–	7.9 ± 0.1	1.10 ± 0.06	0.84 ± 0.05	4884	33	1.14	G16 (G14)
4569590	EB, NO	41.3710 ± 0.0001	0.004 ± 0.001	–	14.1 ± 0.2	1.6 ± 0.10	0.66 ± 0.05	4706	41	1.67	G16 (G14)
4663623	EB	358.09 ± 0.0003	0.43 ± 0.01	54.1 ± 0.2	9.7 ± 0.2	1.36 ± 0.09	0.99 ± 0.08	4812	-	-4.08	G16 (G14)
5006817	HB	94.812 ± 0.002	0.71 ± 0.01	145.9 ± 0.5	5.5 ± 0.1	1.3 ± 0.1	0.199 ± 0.001	5000	-	-2.80	B14
5039392	HB	236.70 ± 0.02	0.44 ± 0.01	6.2 ± 0.1	22.8 ± 0.7	0.8 ± 0.1	?	4110	-	-0.01	B14
5179609	EB	43.93108 ± 0.000002	0.150 ± 0.001	322 ± 1.0	3.50 ± 0.03	1.18 ± 0.03	0.51 ± 0.02	5003	182	-1.96	G16 (G14)
5308778	EB	40.5661 ± 0.0003	0.006 ± 0.005	49 ± 1.1	10.1 ± 0.3	1.5 ± 0.1	0.43 ± 0.03	4900	39	0.80	G16 (G14)
5786154	EB	197.918 ± 0.0004	0.3764 ± 0.0009	29.8 ± 0.2	11.4 ± 0.2	1.06 ± 0.06	0.96 ± 0.07	4747	-	-1.85	G16 (G14)
7037405	EB	207.1083 ± 0.0007	0.238 ± 0.004	21.8 ± 0.1	14.1 ± 0.2	1.25 ± 0.04	0.91 ± 0.03	4516	-	-1.62	G16 (G14)
7377422	EB	107.6213 ± 0.0004	0.4377 ± 0.0005	40 ± 2.1	9.5 ± 0.2	1.05 ± 0.08	0.81 ± 0.07	4938	55	-0.96	G16 (G14)
7943602	EB, NO	14.69199 ± 0.00004	0.001 ± 0.003	–	6.6 ± 0.2	1.0 ± 0.10	0.78 ± 0.09	5096	15	2.70	G16 (G14)
8054233	EB	1058.16 ± 0.02	0.2718 ± 0.0004	46.5 ± 0.3	10.7 ± 0.1	1.60 ± 0.06	0.69 ± 0.04	4971	-	-6.61	G16 (G14)
8095275	HB	23.00 ± 0.01	0.32 ± 0.01	69.3 ± 0.3	7.4 ± 0.1	1.0 ± 0.1	?	4622	-	1.86	B14
8144355	HB	80.55 ± 0.01	0.76 ± 0.01	179.0 ± 2	4.7 ± 0.1	1.1 ± 0.1	?	4875	-	-2.41	B14
8210370	HB	153.50 ± 0.01	0.70 ± 0.01	44.1 ± 0.8	10.0 ± 0.2	1.2 ± 0.1	?	4585	-	-1.92	B14
8410637	EB	408.3 ± 0.5	0.689 ± 0.001	46.0 ± 0.2	10.7 ± 0.1	1.56 ± 0.3	0.85 ± 0.16	4800	-	-4.34	F13
8430105	EB	63.32713 ± 0.00003	0.2564 ± 0.0002	76.7 ± 0.6	7.65 ± 0.05	1.31 ± 0.02	0.63 ± 0.01	5042	122	-0.73	G16 (G14)

Table A.1.: Literature Parameters of red-giant binaries in the *Kepler* sample. (continued)

KIC	Type	P_{orb} [days]	e []	ν_{max} [μHz]	$R/R_\odot$ []	$M/M_\odot$ []	q []	T [K]	P_{rot} [days]	ε_r []	REF
8702921	EB	19.38446 ± 0.00002	0.0964 ± 0.0008	195.6 ± 0.5	5.32 ± 0.05	1.67 ± 0.05	0.16 ± 0.01	5058	98	0.26	G16 (G14)
8912308	HB	20.17 ± 0.01	0.23 ± 0.01	~ 350.0 0	~ 4.0	~ 1.7	?	4872	-	-0.39	B14
9151763	HB	437.51 ± 0.03	0.73 ± 0.01	13.8 ± 0.2	16.7 ± 0.4	1.0 ± 0.1	?	4290	-	-2.62	B14
9163796	HB	121.30 ± 0.01	0.69 ± 0.002	165.3 ± 1.3	5.1 ± 0.1	1.2 ± 0.1	0.985 ± 0.005	4960	130	-3.17	B18 (B14)
9246715	EB	171.27688 ± 0.00001	0.3559 ± 0.0003	106.4 ± 0.8	8.30 ± 0.04	2.149 ± 0.007	0.990 ± 0.005	5030	93	-3.54	R16 (G14)
9291629	EB, NO	20.68643 ± 0.00004	0.007 ± 0.002	–	7.99 ± 0.05	1.14 ± 0.03	0.96 ± 0.03	4713	21	2.26	G16 (G14)
9408183	HB	49.70 ± 0.01	0.42 ± 0.01	164.8 ± 0.2	4.8 ± 0.1	1.0 ± 0.1	?	4900	-	-1.18	B14
9540226	eHB	175.4439 ± 0.0006	0.3880 ± 0.0002	27.1 ± 0.2	12.8 ± 0.1	1.33 ± 0.05	0.74 ± 0.04	4692	-	-1.64	G16 (B14, G14)
9970396	EB	235.2985 ± 0.0002	0.194 ± 0.007	63.7 ± 0.2	8.0 ± 0.2	1.14 ± 0.03	0.89 ± 0.03	4916	-	-3.38	G16 (G14)
10001167	EB	120.3903 ± 0.0005	0.159 ± 0.003	19.9 ± 0.1	12.7 ± 0.3	0.81 ± 0.05	0.98 ± 0.07	4700	-	0.03	G16 (G14)
10614012	eHB	132.13 ± 0.01	0.71 ± 0.01	70.2 ± 0.9	8.2 ± 0.2	1.3 ± 0.1	?	4715	-	-2.23	B14

A.2 Tidal properties of selected systems

Table A.2 lists the following parameters for the systems' red-giant primary with known P_{rot},

- δ_{10} is the 10^{th} percentile of the logarithm of the ratio between the dissipation of the equilibrium and the dynamical tide, $\delta = \log(\mathcal{D}_{\mathrm{eq}} / <\mathcal{D}>_{\omega})$.

- $\tau_{\mathrm{conv},10}$ is the corresponding convective turnover timescale computed in the middle of the convective zone.

- $P_{\mathrm{tide}} > \tau_{\mathrm{conv},10}$ indicates if the tidal period is longer than the convective turnover timescale (Yes / No).

Table A.2.: Evolution of δ_{10} for the systems with know rotation period.

KIC	P_{tide} [days]	$\tau_{\mathrm{conv},10}$ [days]	$P_{\mathrm{tide}} > \tau_{\mathrm{conv},10}$	δ_{10}
7943602	357	20	Y	2.3-3.4
7377422	56	20	Y	3.7-4.8
3955867	845	20-23	Y	2.6-3.7
9291629	692	20-23	Y	2.3-3.4
5179609	28	23	Y	4.7-5.8
9163796	906	23	Y	3.8-4.9
8430105	65	23-26	Y	4.4-5.5
5308778	505	12	Y	3.0-4.1
4569590	2285	12	Y	2.4-3.5
8702921	12	12	N	4.2-5.3
9246715	101	14	Y	4.1-5.2

B Example for the presentation of programming code

B.1 System dependencies

The presented code is written for Python 3.7. Table B.1 details the used standard and specialized python packages and modules and is structured as follows.

- The package and module names are listed in the first column. Specialized modules are preceded with the abbreviation of the parent package, whose abbreviated package name is indicated in brackets.
- The version number of the used library is indicate in the second column.
- A brief module description is provided in the third column.

The top panel reports the standard python packages, contained in the standard python distribution. The bottom panel lists specialized packages, which require individual download. (Modified table based on Table A.1 from Rafael Goldgruber's Bachelor thesis).

Table B.1.: Required Python modules for the presented code.

Package / Module	Version	Modul Description
math	–	Access mathematical functions;
os	–	Miscellaneous operating system interfaces
glob	–	Creates iterable lists from folder content
matplotlib	3.3.1	Core package for scientific computation & plotting
numpy	1.19.1	Core package for numerical computing
astropy (ap)	4.0.1	Community Python Library for Astronomy
ap.astroquery	0.4	Querying astronomical web databases
ap.vizier	0.4	Importing online data and catalogues, published along with papers
ap.io.pyfits		Reading and operating with FITS files
mesareader	–	Reading MESA history and profile output files

B.2 Program to name new Planets

Provide a short description of the following script and give a brief description of the key settings or input format. The example below shows how to insert the code of a whole program from its source file.

Listing B.1: HelloPlanet.py: Sophisticated code to name new worlds.

```
import sys,os,math
import numpy as np
import pylab as pl

# here we have a comment on the scripting

for iii in np.arange(0,42):
  print('Hello␣new␣planet␣number␣{}'.format(iii+1))
```

Table B.2.: Option menu for helloWorld.py (Listing B.1),

Type	Argument	Functionality
InCode	if xY==True	Description of what will happen if this option is used.
CmdL	-n	Description of what will happen if this option is used.
ReqIn	parameter name	Description of what will happen if this option is used.

Notes. Usage options: *InCode* curial options to be set inside the code before excecution of the program, *CmdL* options set in the command line, *ReqIn* requested user input during the execution of the program;

B.3 Example for long code listing

This section presents styles to present longer code snippets. To save printing space and cost, these are typset in a two-column format.

The combined presentation of Listing B.2 and Listing B.3 show how two snippets can be shown. Listing B.4 depicts how long code snippets or full programs can be included as multi-column and multi-page element.

Also for these listings a preamble stating the system requirements is needed.

Listing B.2: inlist1

```
&star_job
       show_log_description_at_start = .true.
       pgstar_flag = .true.
/ ! end of star_job namelist

&controls
       extra_terminal_output_file = 'log1'
       log_directory = 'LOGS1'
/ ! end of controls namelist

&pgstar
       History_Panels1_win_flag = .true.
       History_Panels1_win_width = 5
       History_Panels1_win_aspect_ratio = 1.0

       History_Panels1_title = 'Orbital_evolution'
       History_Panels1_num_panels = 2

       History_Panels1_yaxis_name(1) = 'period_days'
       History_Panels1_other_yaxis_name(1) =
       'lg_mstar_dot_1'
       History_Panels1_yaxis_name(2) = 'Jdot'
       History_Panels1_other_yaxis_name(2) =
       'binary_separation'
/ ! end of pgstar namelist
```

Listing B.3: inlist2

```
&star_job
       show_log_description_at_start = .false.

/ ! end of star_job namelist

&controls
       extra_terminal_output_file = 'log2'
       log_directory = 'LOGS2'
/ ! end of controls namelist

&pgstar

/ ! end of pgstar namelist
```

Listing B.4: Example for a multi-column and multi-page code listing.

```
! inlist to evolve a 15 solar mass star

! For the sake of future readers of this file,
! ONLY include the controls you are actually using.
! DO NOT include all of the other controls that
! simply have their default values.

&star_job

  ! begin with a pre-main sequence model
    create_pre_main_sequence_model = .true.

  ! save a model at the end of the run
    save_model_when_terminate = .false.
    save_model_filename = '15M_at_TAMS.mod'

  ! display on-screen plots
    pgstar_flag = .true.

/ !end of star_job namelist


&controls

  ! starting specifications
    initial_mass = 15 ! in Msun units

  ! options for energy conservation
     use_dedt_form_of_energy_eqn = .true.
     use_gold_tolerances = .true.

  ! stop when the star nears ZAMS (Lnuc/L > 0.99)
    Lnuc_div_L_zams_limit = 0.99d0
    stop_near_zams = .true.

  ! stop when the center mass fraction
  of h1 drops below this limit
    xa_central_lower_limit_species(1) = 'h1'
    xa_central_lower_limit(1) = 1d-3

/ ! end of controls namelist

&pgstar

  ! MESA uses PGPLOT for live plotting and
  ! gives the user a tremendous amount of control
  ! of the presentation of the information.

```

```
  ! show HR diagram
  ! this plots the history of L,Teff over many
  ! timesteps
    HR_win_flag = .true.

  ! set static plot bounds
    HR_logT_min = 3.5
    HR_logT_max = 4.6
    HR_logL_min = 2.0
    HR_logL_max = 6.0

  ! set window size (aspect_ratio = height/width)
    HR_win_width = 6
    HR_win_aspect_ratio = 1.0


  ! show temperature/density profile
  ! this plots the internal structure at single
  ! timestep
    TRho_Profile_win_flag = .true.

  ! add legend explaining colors
    show_TRho_Profile_legend = .true.

  ! display numerical info about the star
    show_TRho_Profile_text_info = .true.

  ! set window size (aspect_ratio = height/width)
    TRho_Profile_win_width = 8
    TRho_Profile_win_aspect_ratio = 0.75

/ ! end of pgstar namelist
```

Appendix C

C

Curriculum Vitae
Mag. Nikolaus Copernicus, PhD

Born	February 19, 1473
Citizenship	Poland

Research positions and academic education

Current academic position

Affiliation & academic address	Institute for Physics, Karl Franzens University Graz, Universitätsplatz 5/II, NAWI Graz, 8010 Graz, Austria
Contact	nicolaus.copernicus@uni-graz.at

Research Positions

since March 2020	Doctoral researcher at the Department for Astronomy, Inst. of Physics, NAWI Graz, University of Graz, Austria
2019, March – 2020, March	Pre-doctoral researcher at the Department for Astronomy, Inst. of Physics, NAWI Graz, University of Graz, Austria

Academic Education

2017, February – 2019, March	University of Graz, Austria: Master of Natural Sciences in Physics (Graduation: March 32, 2019), Title of Thesis
2014, October – 2017, February	University of Vienna, Austria : Bachelor of Natural Sciences in Astronomy (Graduation: February, 30, 2017)

Academic Recognition

Invited talks at conferences and seminars

- **Title of invited contribution**, title of conference or occasion, length of contribution, (date, hosting institution)

Grants & Awards

- **Name of achievement**, awarding entity or agency, (awarded amount, duration)

Service to the community & memberships in academic organization

- **Refereeing activity for scientific journals**, give concise details

- **Membership in relevant professional societies, consortia or collaborations**, give concise details

- **Function in associations**, give concise details

Extended scientific or exchange stays

- Institution, program / purpose, give concise details

Teaching Portfolio

List here the courses you have assisted in or taught until now.

- **Name of Course**, (type of course: e.g. lecture, exercises, practicum, ...) Semester 202X, ECTS of the course, Bachelor's / Master's Curriculum, list your co- or lead-lecturer, description of your responsibilities in this course.

- **Name of Course**, (type of course: e.g. lecture, exercises, practicum, ...) Semester 202X, ECTS of the course, Bachelor's / Master's Curriculum, list your co- or lead-lecturer, description of your responsibilities in this course.

Nota bene: If you use this template for your Habilitationsschrift, replace this section by the structure and content of the teaching portfolio, as recommended[1] by the *Zentrum für Lehrkompetentz (ZLK) of Graz University.*

Observing Portfolio

The candidate has obtained XXX nights of accumulated observing experience of at international facilities:

- Observatory name and location, telescope, technique, number of nights

Proposals lead as Principle investigator

- **Title of successful proposal**, awarded observing time (observing semester), observatory, telescope & instrument specification

Proposals contributed to as Co-investigator

- **Title of successful proposal**, awarded observing time (observing semester), name of PI, observatory, telescope & instrument specification

[1] https://lehrkompetenz.uni-graz.at/de/service/lehrportfolios/

List of Publications

Bibliographic information and overview

Repository identifiers	ORCID: xxx, GitHub: xxx
Bibliometric indicators	H-index: xxx, m-index: xxx
Publication record in NASA ADS	URL of your private NASA ADS library

Refereed journal publications

Published work that is available as open access through the ArXiv.org preprint server or journal policies is indicated through the abbreviation [AO].

1. **Your, N.**, Author, A., Author, B., Author, C., ... , **Title of the paper**, Journal, Volume, pages, DOI, (Year) [AO]

2. Author, A., Author, B., **Your, N.**, Author, C., ... , **Title of the paper**, Journal, Volume, pages, DOI, (Year) [AO]

Conference proceedings and other publications

1. **Your, N.**, Author, A., Author, B., Author, C., ... , **Title of the conference proceedings paper**, Conference Series, pages, DOI, (Year) [AO]

2. Author, A., Author, B., **Your, N.**, Author, C., ... , **Title of the popular paper**, Popular Journal, Volume, pages, DOI, (Year) [AO]

Colophon

This thesis was typeset with $\LaTeX\ 2_\varepsilon$. It uses the *Clean Thesis* style developed by Ricardo Langner, available at http://cleanthesis.der-ric.de/. The design of the *Clean Thesis* style is inspired by user guide documents from Apple Inc.

The template is provided in this adapted version by Desmond Grossmann, BSc, Stefan Janisch, BSc, Lea Schimak and Paul Beck, PhD to implement the editorial guidelines of *Astronomy & Astrophysics* and the cooperate-identity guidelines of the University of Graz for the Institute for Physics. Version: March, 2024.

Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to UNIGRAZonline or TUGRAZonline is identical to the present master's thesis.

Graz, May 14, 2025

Markus Ornik