

Relating spot and flare/superflare occurrence on dwarf stars

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May 18, 2025



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-
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Mag. Dr.rer.nat. Martin Leitzinger

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

Unsubmitted Thesis Manuscript: compiled on May 18, 2025

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Abstract

Context.

Aims.

Methods.

Results.

Conclusions.

Acknowledgement

I gratefully acknowledge my supervisors Assoz. Prof. Mag. Dr.rer.nat. Manuela Stadlober-Temmer and Mag. Dr.rer.nat. Martin Leitzinger for guiding me through the process.

I thank my family and friends for supporting me.

This thesis made use of the experimental setups, laboratory and technical infrastructure, general resources and observational facilities of the Institute of Physics of the University of Graz. This thesis also made use of infrastructure, which was supported by NAWI Graz.

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.

I gratefully acknowledge the Austrian Science Fund (FWF): P30949-N36 (PI: xxx) for supporting this project.

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Introduction

1.1 Current knowledge

1.2 Spectral Types

1.3 Flares and Starspots

1.4 Space missions

Thompson et al. (2012).

Kepler 6

$$c^2 = a^2 + b^2, \quad (1.1)$$

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

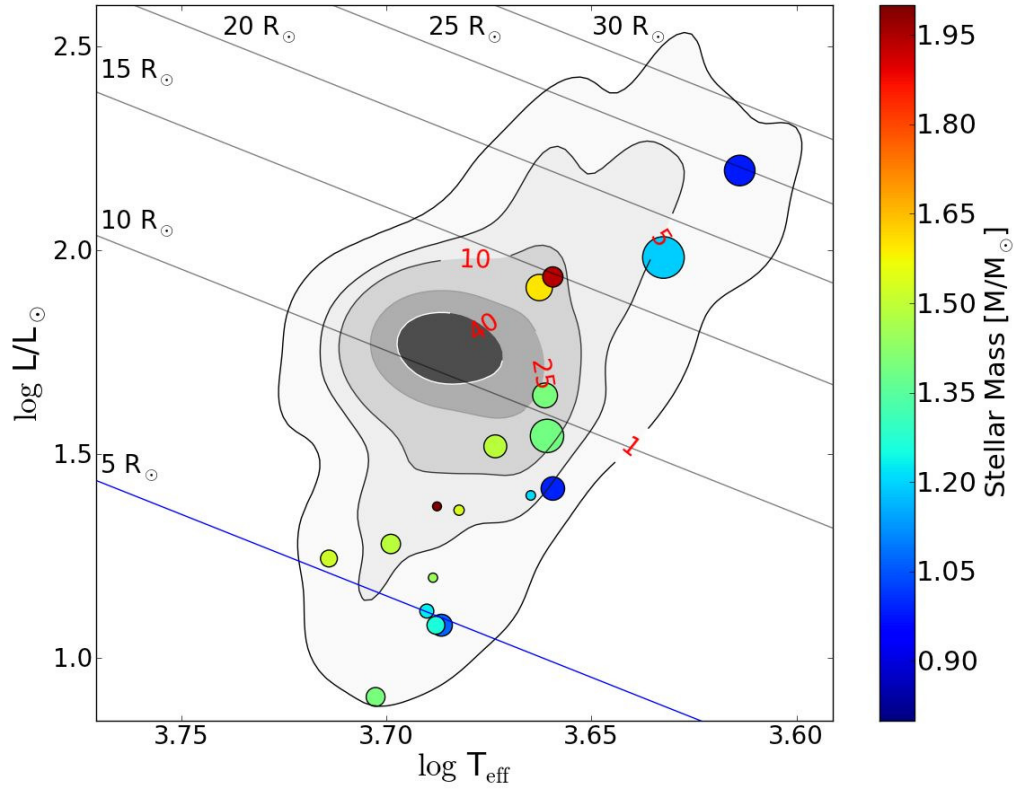


Fig. 1.1.: Position of the 18 red giant heartbeat stars from Tables 1 and 2 in the HR diagram, where the colour shows the mass of the red giant, derived from seismology. The size of the dots represents the orbital period, ranging between 20 and 438 d. The contour surfaces reflect the density distribution 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 $R_{\odot}$. (Figure taken from Beck et al., 2014)

GUI

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 separated 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 differences 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 then 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),

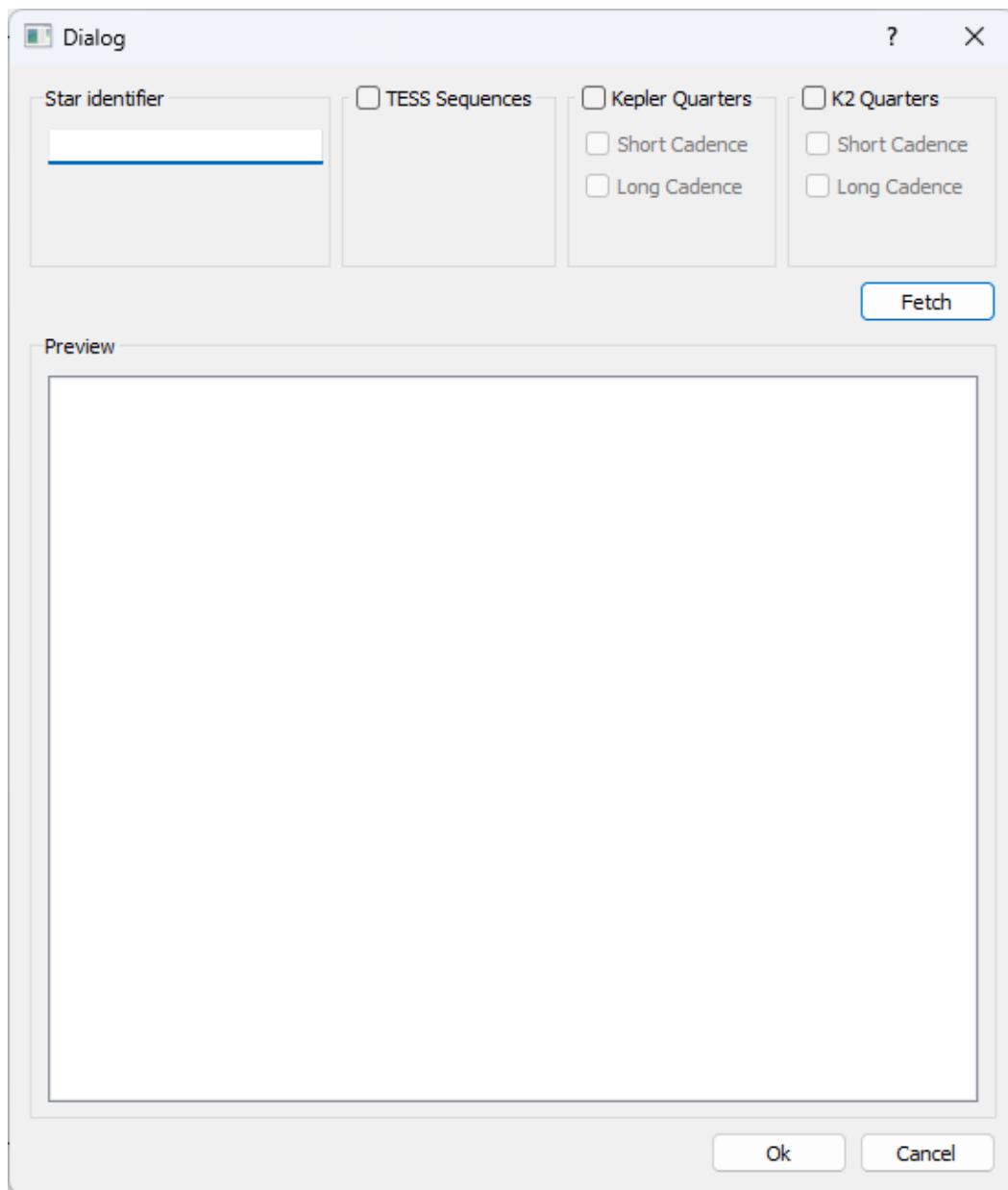


Fig. 2.1.: GUI window for downloading new fit files with astroquery designed using the Qt5 designer shipped with PyQt5 (Riverbank Computing Limited (2025)). The star identifier field supports one or more (separated by a semicolon) identifiers. There are checkboxes to select TESS, Kepler (long and/or 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 formatting 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.

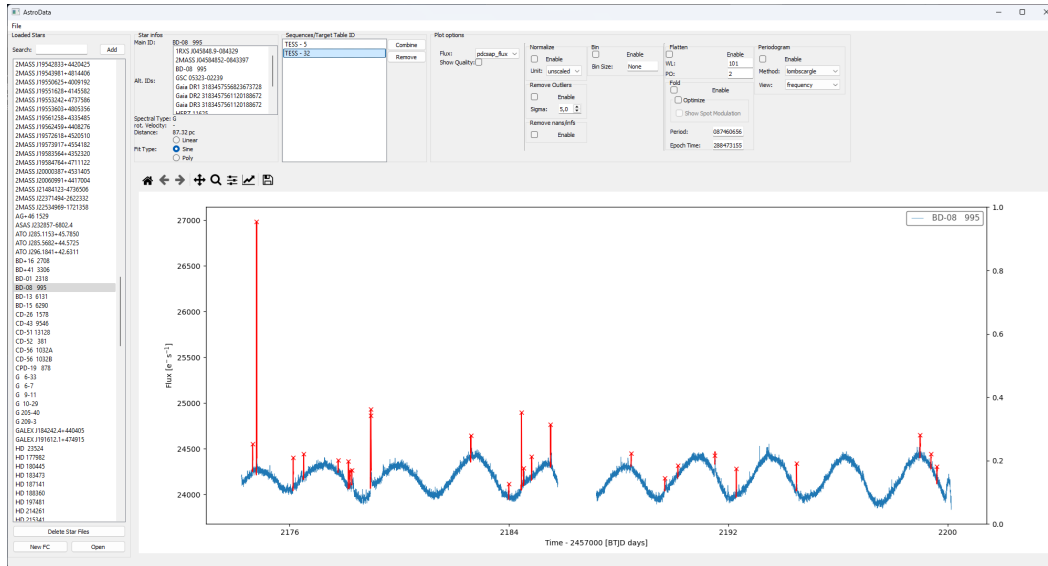


Fig. 2.2.: Main GUI window. This window was designed with the Qt5 designer shipped with PyQz5 (Riverbank Computing Limited (2025)). It shows a list of all available stars with their main identifier (taken from SIMBAD (Wenger et al. (2000))) sorted alphabetically. The "Star infos" box contains additional information on the star gathered from SIMBAD. There is a list of alternative IDs, the spectral type, the rotational velocity, and the distance. It also shows the preferred 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 lightcurve python package (Lightcurve 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.

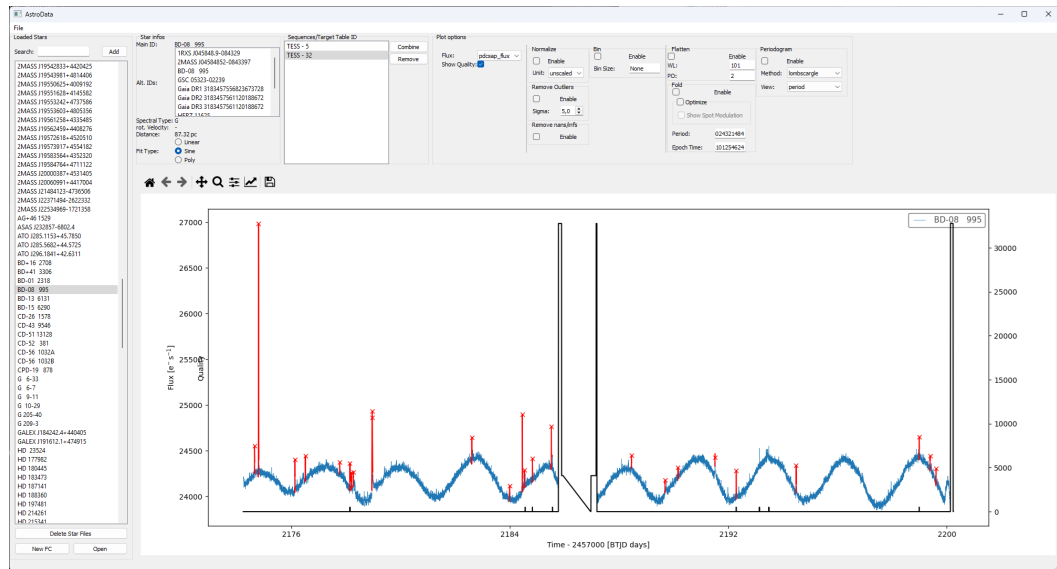


Fig. 2.3.: Main GUI window. Same as in figure 2.2, with the difference that the data quality flag is also shown.

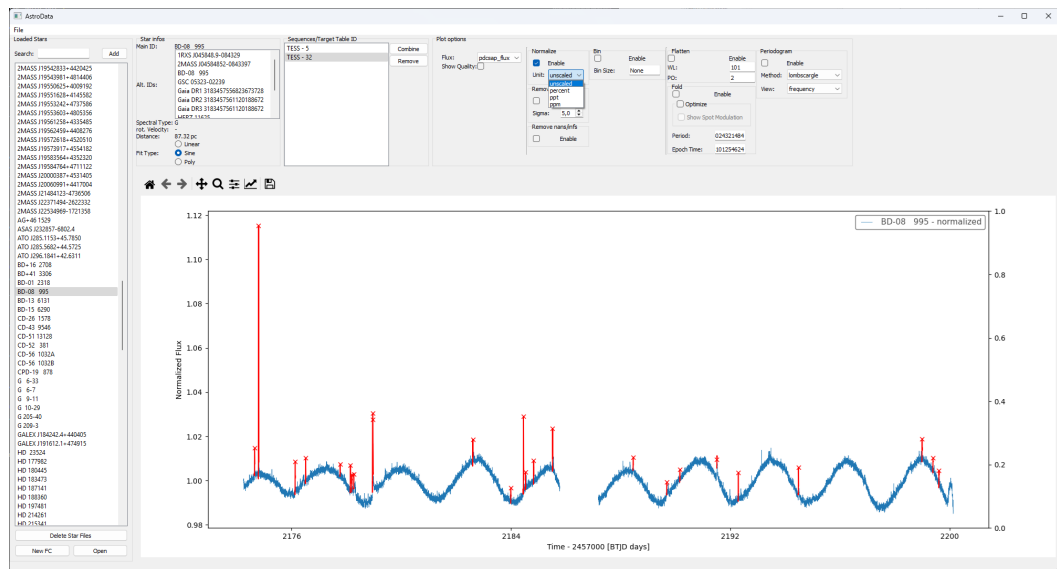


Fig. 2.4.: Main GUI window. Same as in figure 2.2, with the difference that the lightcurve was normalized. It also shows all possible normalize options the lightcurve python package (Lightcurve Collaboration et al. (2018)) supports.

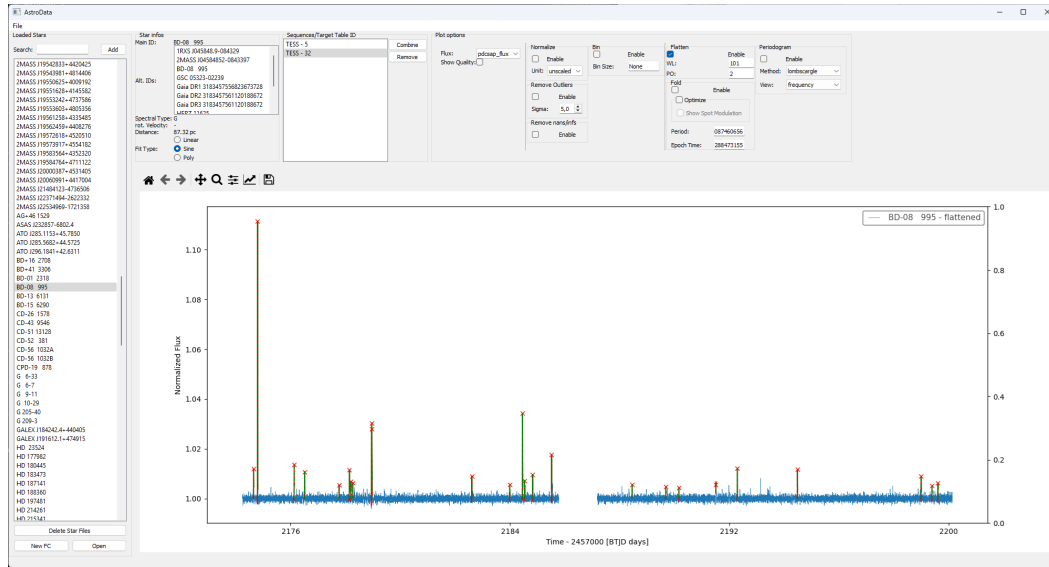


Fig. 2.5.: Main GUI window. Showing the same lightcurve as figure 2.2, with the difference that it is now flattened. The green line shows a fit of the flare. This is described in chapter 3.2.

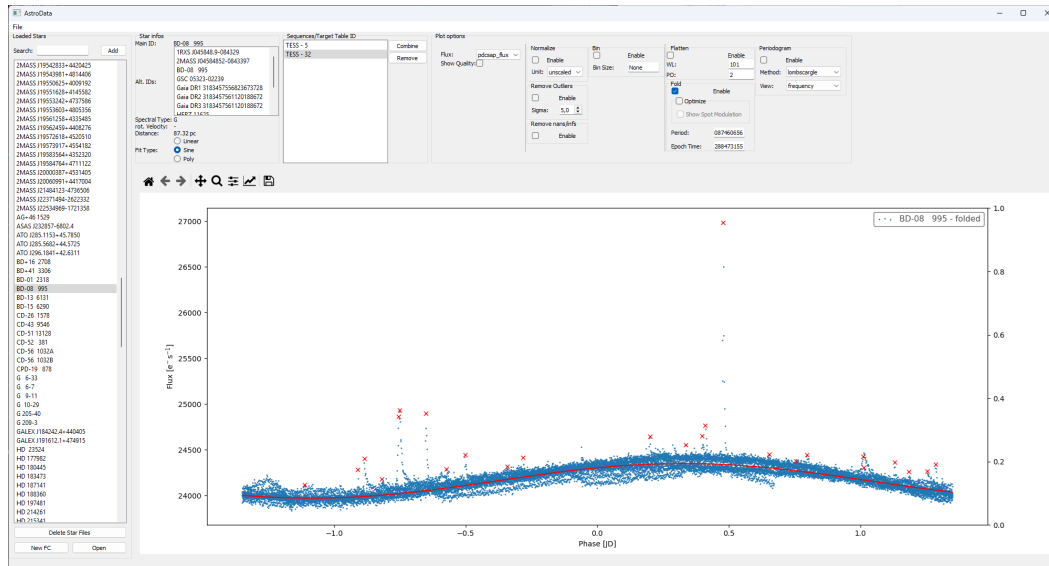


Fig. 2.6.: Main GUI window. Showing the same lightcurve as figure 2.2, with the difference that it is now folded with an period of 2.697 days. Additionally vertical lines are shown which indicate the region around the minima and maxima of the folded lightcurve respectively.

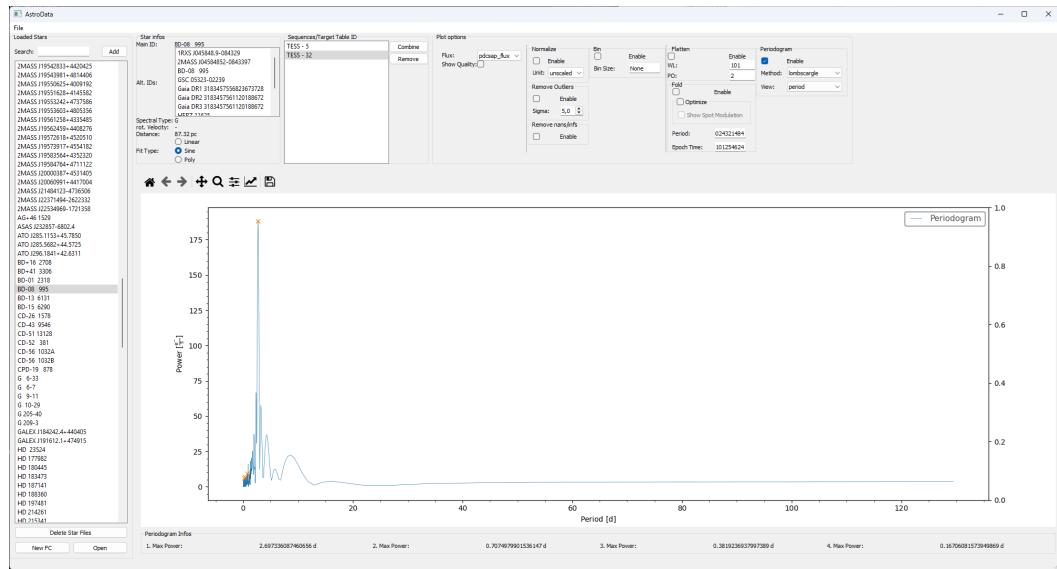


Fig. 2.7.: Main GUI window. Showing the periodogram of the lightcurve in figure 2.2 using the lombscargle algorithm. Furthermore it shows the four highest peaks (which are atleast 100 datapoints separated). The method is explained in chapter 3.2.

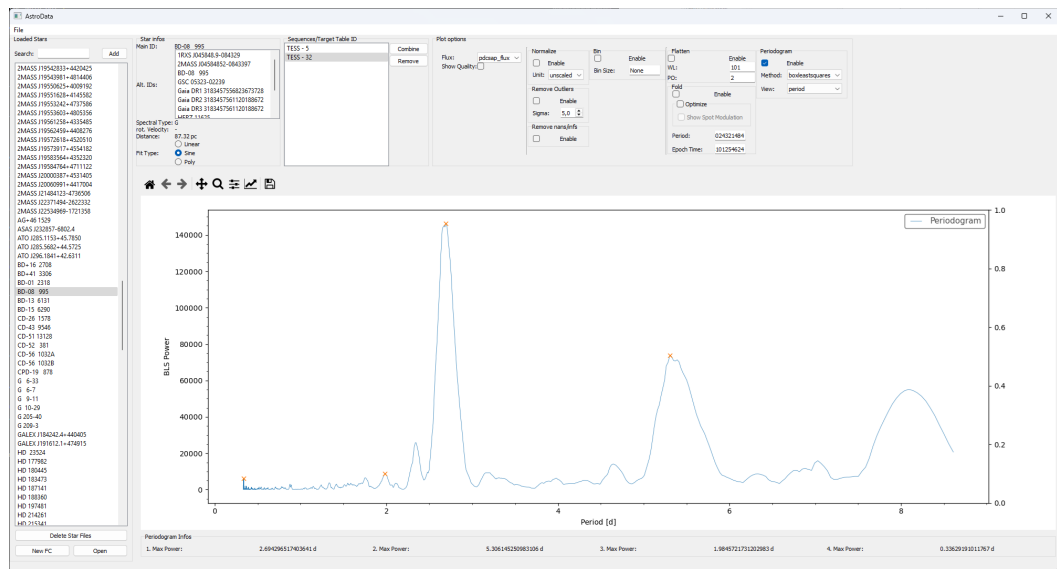


Fig. 2.8.: Main GUI window. Showing the periodogram of the lightcurve in figure 2.2 using the box least square algorithm. Similarly to figure 2.7 the four highest peaks are marked with a red 'x'.

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 separately save 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 $\sim 10\%$, 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 in 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

3.3 Spectral type identification

3.3.1 This is a subsection

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.

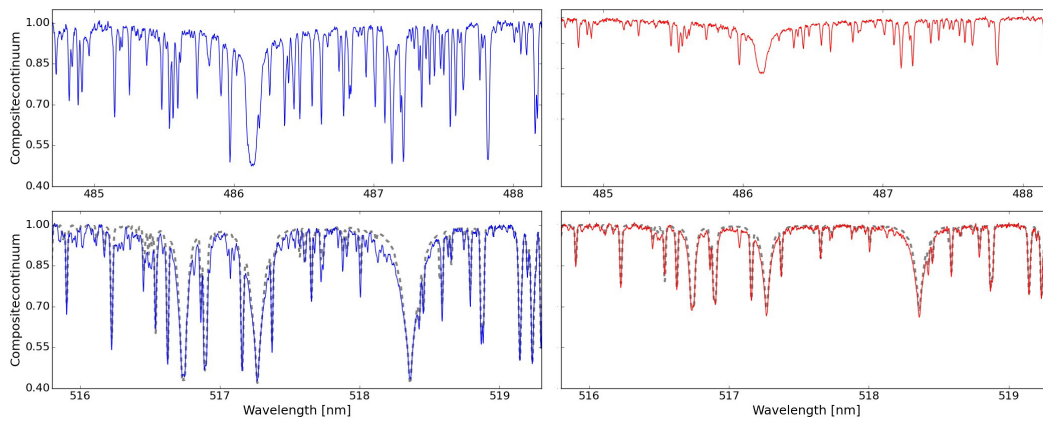


Fig. 3.1.: Disentangled spectra of KIC 9163796. The spectra of the primary in blue and secondary in red are shown in the left and right spectrum, respectively. Top panel: the region around the H β line, while bottom panel: magnesium triplet at 518 nm, normalised to the continuum flux of the composite 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)

3.4 Example of a code snippet

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

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

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 contain plots for the different spectral types M, K, G, and F as well as combined results of every possible combination. Additionally for all these possible combinations, plots with data limits, e.g. only stars with a rotational period of less than 2 days or minimal/maximal normalized flare peak limits, were also generated. Additionally plots for stars with a more detailed spectral type like M0 or G5 were created. Furthermore there is a selection of individual star results. For every plot group a CSV file is generated, which contains information about every star and flare used to generate the plot. 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 as well as all plots and the accompanying CSV files are available at [google drive](#).

4.1 M dwarfs

This section shows the results for all 144 M dwarfs in this study. The list of stars can be found in table A.1.

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 an even distribution within error of flares across the normalized phase, with the exception of the bin at phase 0.5π . The bin at phase 0.5π shows a significant dip of roughly twice the error below the surrounding bins.

Looking at the same data, just with 30 instead of 10 bins (figure 4.2), the same dip is visible. In this figure the dip spans 3 bins. Additionally there are additional dips at around phase 0.7π , 1.3π and 1.4π . Including the error, the major dip (which was already visible in figure 4.1) is still below the average. Similar for the dips at phases 0.7π and 1.3π . The dip at phase 1.4π on the other hand overlaps with its error with the errorbars of the bins at phase $\sim 1.7\pi$ and onward, which are good assumption for an average value. Due to the dips surrounding the center, it may look like there is an increased number of flares in the center. If we look at the errorbars, it is clear that only the bin at phase $\sim 1.25\pi$ is above the average.

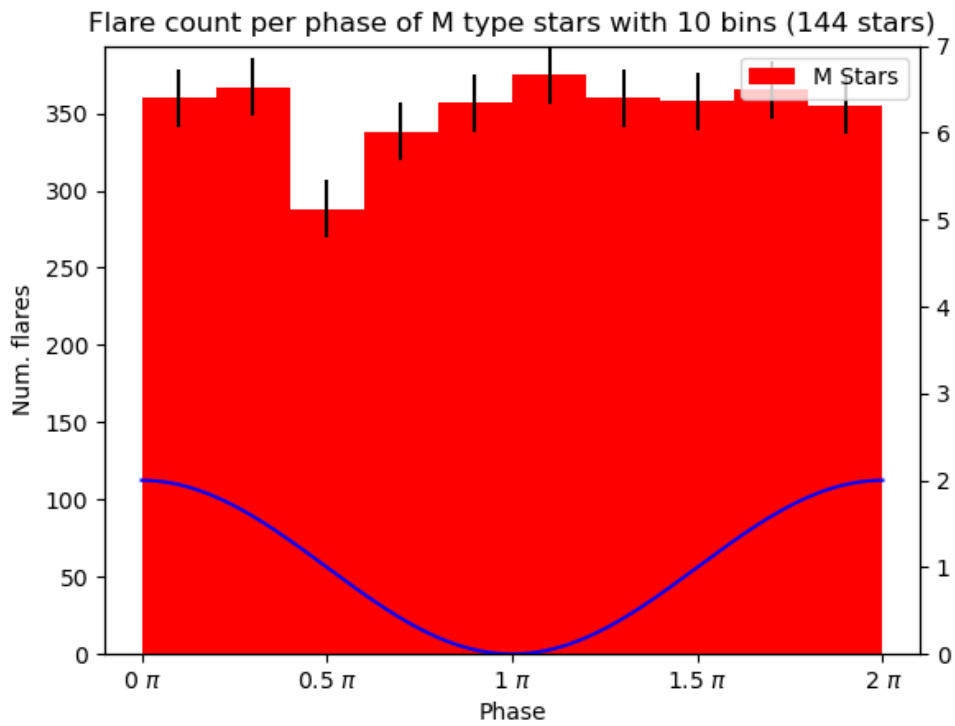


Fig. 4.1.: Histogram showing the amount of flares per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

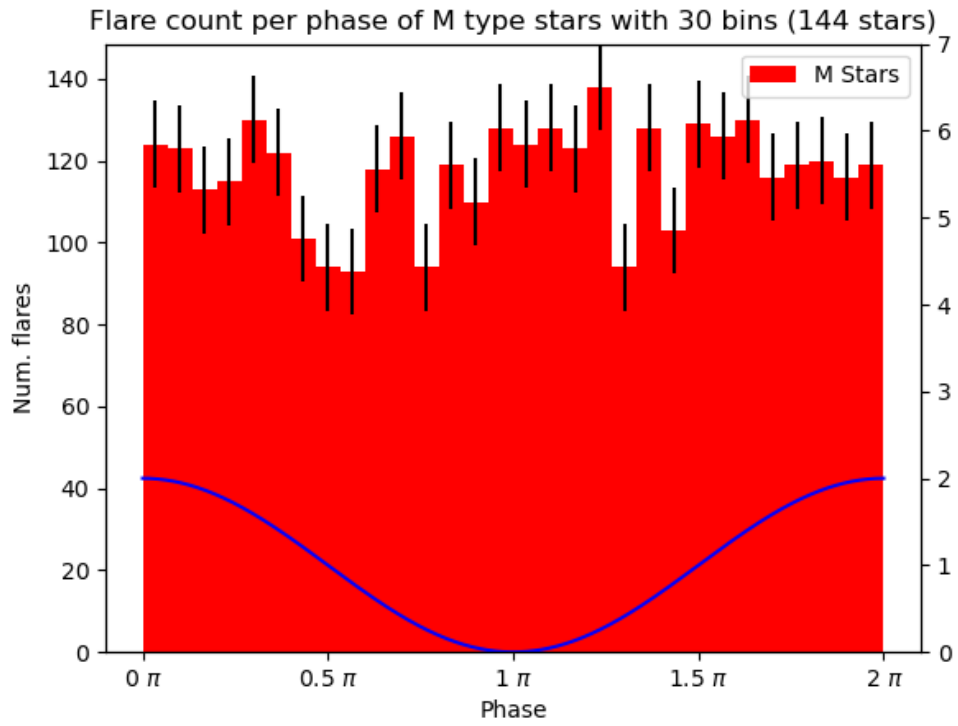


Fig. 4.2.: Histogram showing the amount of flares per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 30 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

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 increasingly more flares in the minima at phase 1π (more/bigger star spots) and maxima at phase 0 and 2π (less/smaller star spots) compared to the transitions. Taking a closer look at figure 4.3, which accounts only for normalized flare peaks greater than 1.25 with 10 bins, the same dips (around phases 0.5π and 1.5π) as in the previous figure (figure 4.2) are visible. Comparing to the dip visible in figure 4.1, it widened by 1 bin. At phase $\sim 1.7\pi$ to 2π there is a major peak. While the last bin overlaps slightly with the one at phase 0.9π with accounting for error, the second to last does not.

The same data, just with 30 bins can be seen in figure 4.4. There are no continuous peaks like in the previous figure, but at the same phases there are bins with an increased number of flares. Additionally, at around phase 0.6π , there is a larger amount of flares compared to the bins next to it.

Increasing the normalized minimal flare peak further to 1.5 decreases the total amount of flares further, which results in a comparatively large error. This makes the error half the size or even larger than some of the bins in figure 4.5. Nonetheless it is visible that the largest flares seem to appear more often around phase 1π and phase $0\pi/2\pi$. Including the error, those peaks are still higher than the flare count of the in previous figures mentioned dips.

Increasing the bin count to 30 (see figure 4.6) decreases the individual bin heights so far, that the errorbars start to explode in size, which causes all of them to overlap and not give any proper results.

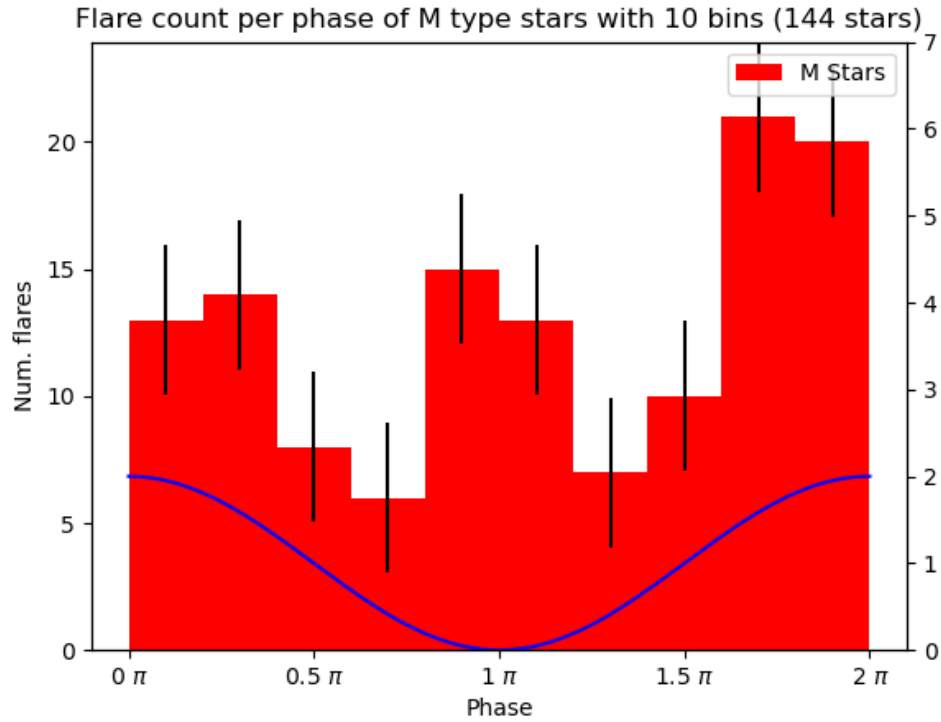


Fig. 4.3.: Histogram showing the amount of flares with a normalized peak of greater than 1.25 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

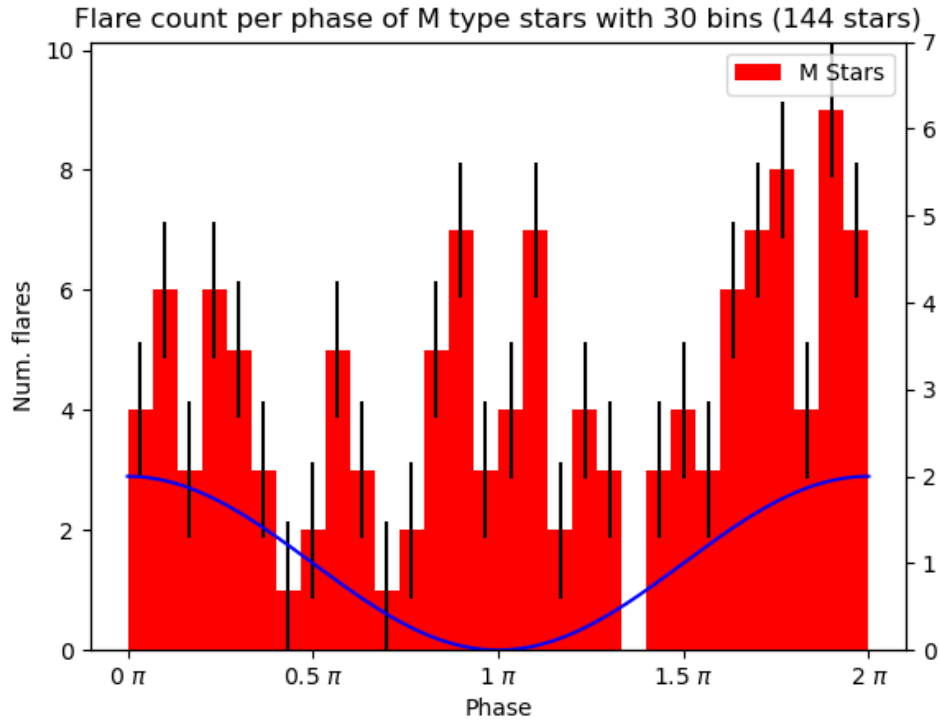


Fig. 4.4.: Histogram showing the amount of flares with a normalized peak of greater than 1.25 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 30 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

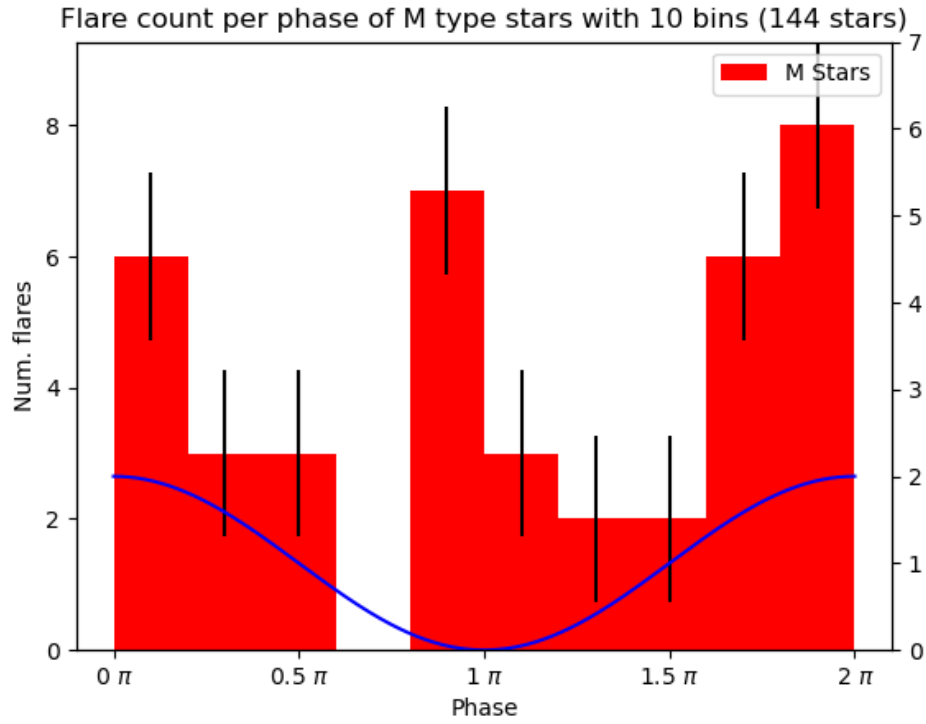


Fig. 4.5.: Histogram showing the amount of flares with a normalized peak of greater than 1.5 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

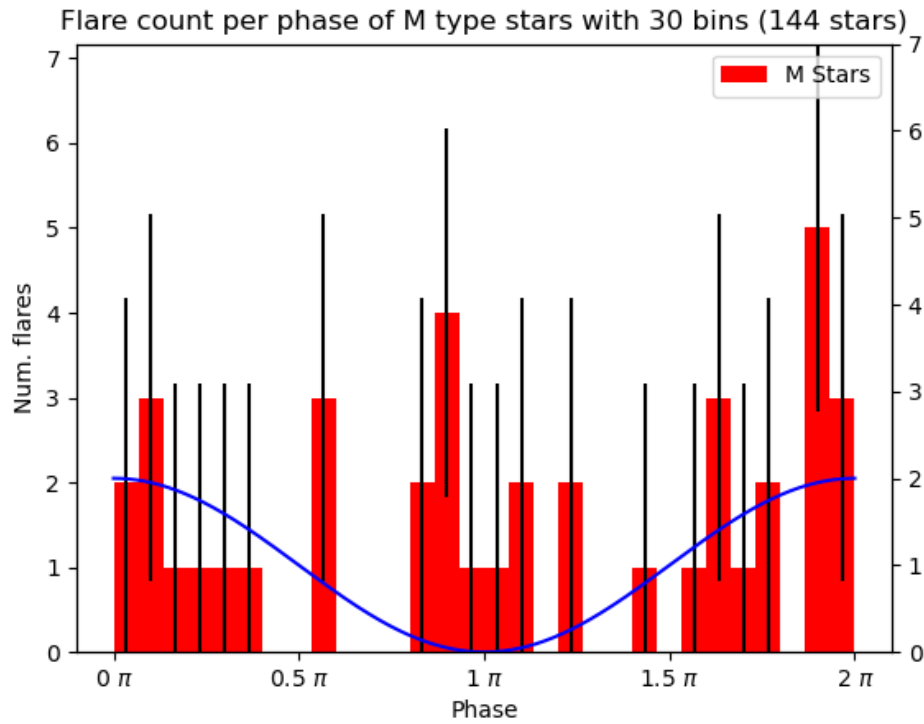


Fig. 4.6.: Histogram showing the amount of flares with a normalized peak of greater than 1.5 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 30 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

4.2 K dwarfs

This section shows the results for all 37 K dwarfs in this study. A full list of the stars used can be found in table A.2.

Figure 4.7 shows the amount of flares per phase with 10 bins of 37 K type dwarfs in used in this study. Overall the distribution is even within error, with a slight increase in flares when going from the maximum to the minimum of the lightcurve at phase 0.5π , and a slight decrease when going from minimum to maximum at phase 1.5π . There is also a peak at around 1π with around 95 flares compared to the 60-80 flares per bin in the rest of the histogram. This peak is dominated by $V * V471 Tau$. The individual results for this star are visible in section 4.6.

Looking at the same dataset with 30 bins for the histogram (figure 4.8), the peak in the phase minimum at 1π is still visible. Additionally there appear more peaks at phase $> 1.3\pi$ (1.3, 1.6, 1.9π), while the amount of flares between phase 0π and 1π shows a slight trend to more flares with dips inbetween and a larger dip right before and after the big peak at phase 1π which was also visible in figure 4.7 with 10 bins. The major dips at phase 0.7π , 1.3π , 1.6π and 1.9π are all well outside the errorbars of the surrounding peak bins, while the smaller ones between phase 0π and 1π overlap with their errorbars with their surrounding bins.

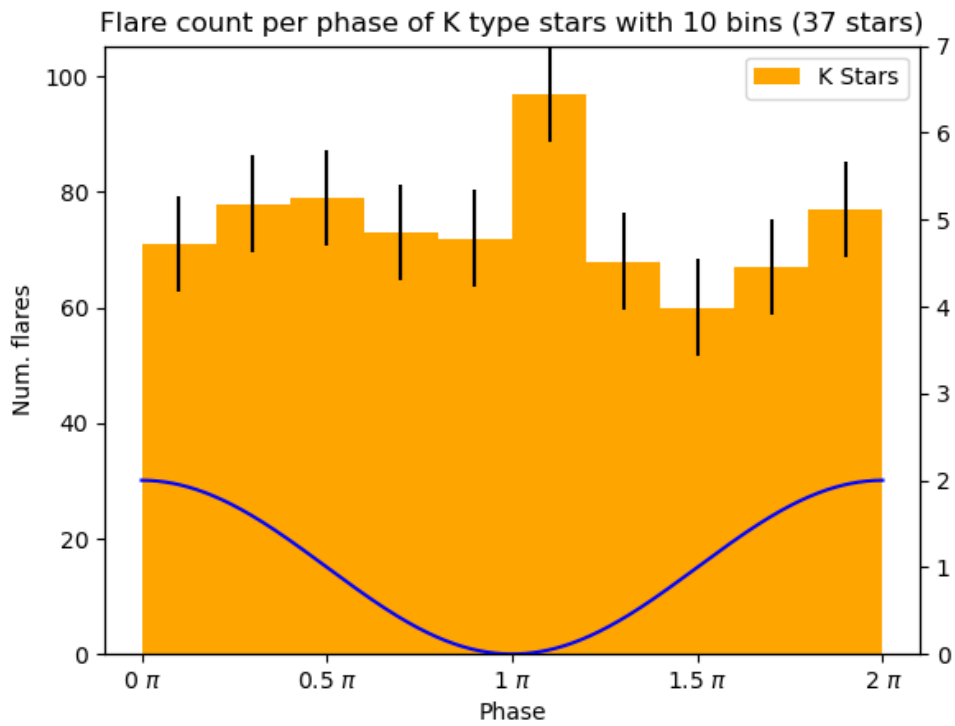


Fig. 4.7.: Histogram showing the amount of flares per phase for all 37 K dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

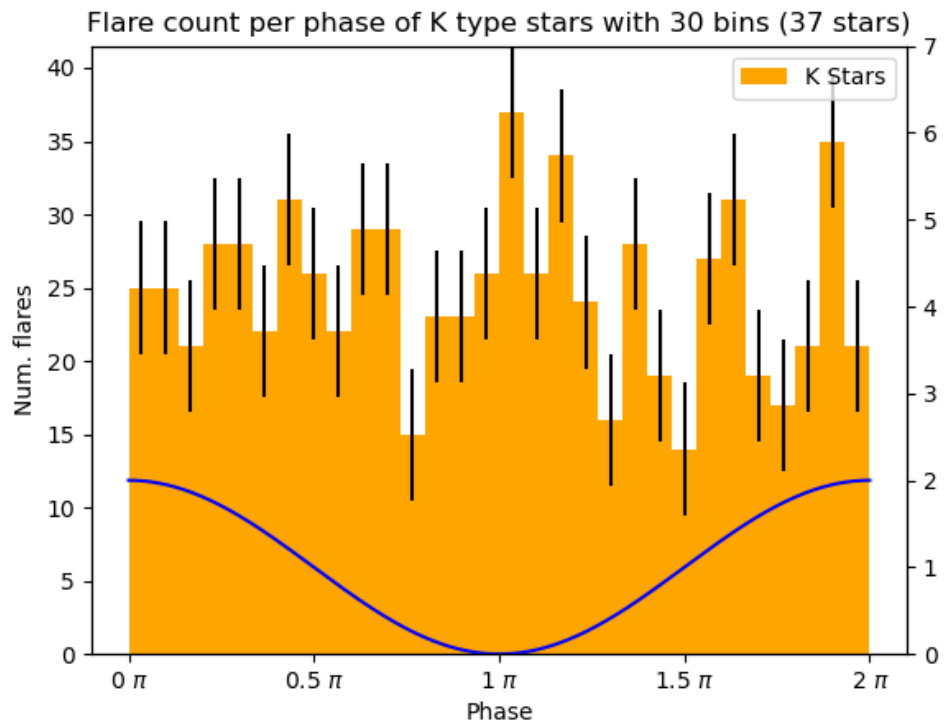


Fig. 4.8.: Histogram showing the amount of flares per phase for all 37 K dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 30 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

4.3 G dwarfs

This section shows the results for 71 G dwarfs in this study. Table A.3 contains a list of all G type stars used.

The first histogram over all data of G type dwarfs with 10 bins in figure 4.9 shows a significant increase of occurring flares well outside the errorbar range in the lightcurve minima at around phase 1π compared to the maxima at phase $0\pi/2\pi$. The rise in flare occurrences from maxima to minima (phase 0π to 1π) seems to be gradual, while there is a steep fall off after the sixth bin at phase 1.1π .

Due to the lower number of detected flares on G type stars, the error bars in figure 4.10 are rather large. The increase of flares in the minima of the folded lightcurve from the previous figure is now split into two peaks at phase 0.6π and 1π . An additional peak bin appears at around phase 0.25π in this figure. This peak's errorbar does not overlap with its surrounding bins' errorbars. Right before this peak is a significant dip visible at phase 0.2π . On the other half of the phase after the peak at phase 1π , the near even distribution of figure 4.9 becomes more noisy, even though it's still well within error.

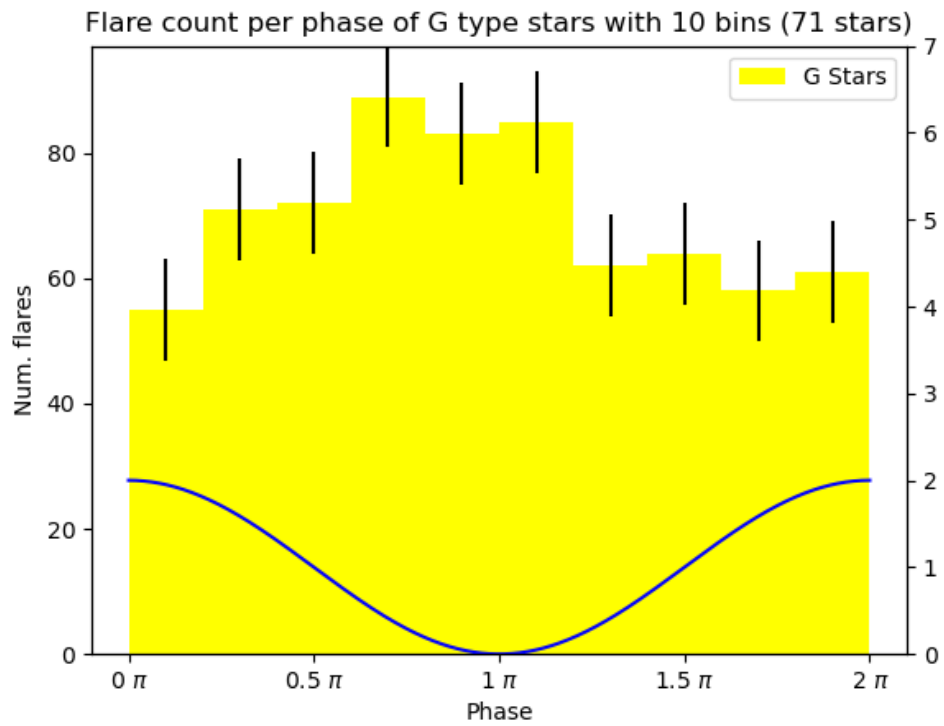


Fig. 4.9.: Histogram showing the amount of flares per phase for all 71 G dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

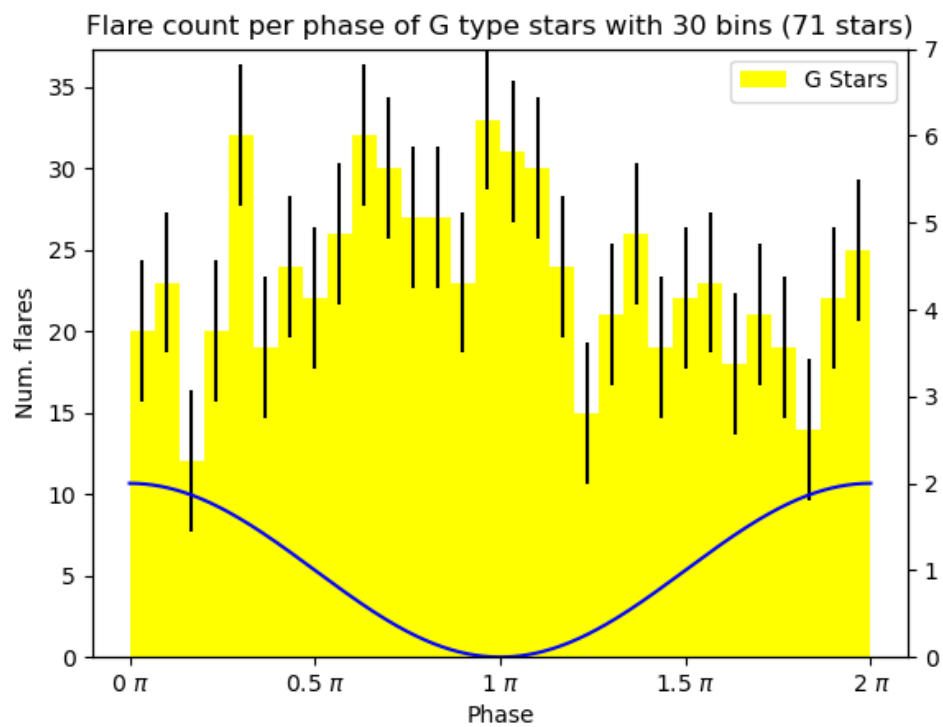


Fig. 4.10.: Histogram showing the amount of flares per phase for all 71 G dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 30 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

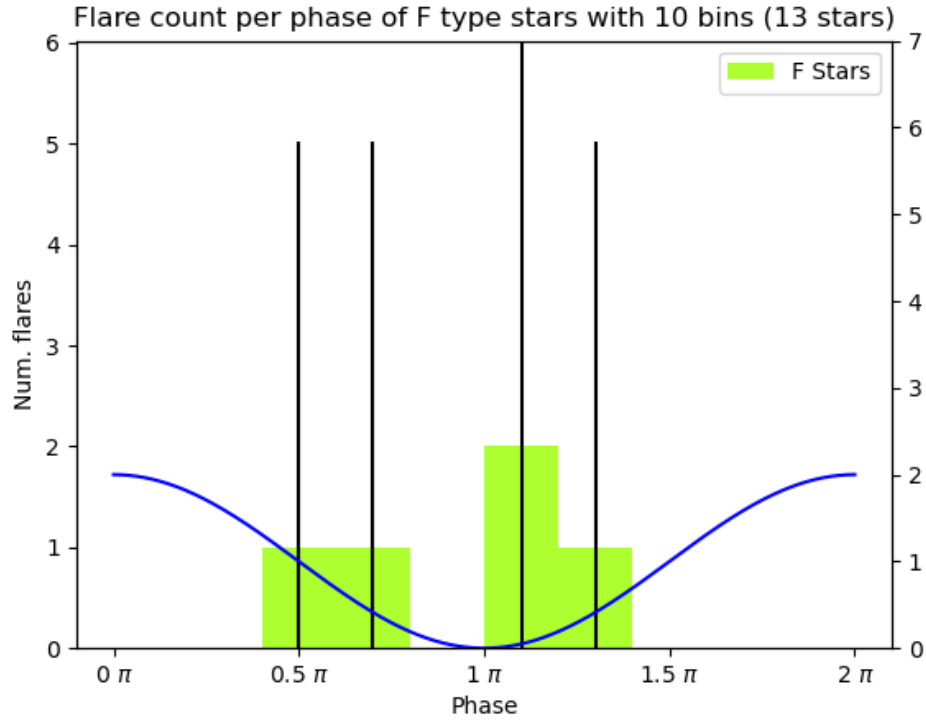


Fig. 4.11.: Histogram showing the amount of flares per phase for all 13 F dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

4.4 F dwarfs

This section shows the results for all 13 F dwarfs in this study. The list of F type stars can be found in table A.4.

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. Nonetheless all detected flares were around the minimum of the lightcurves.

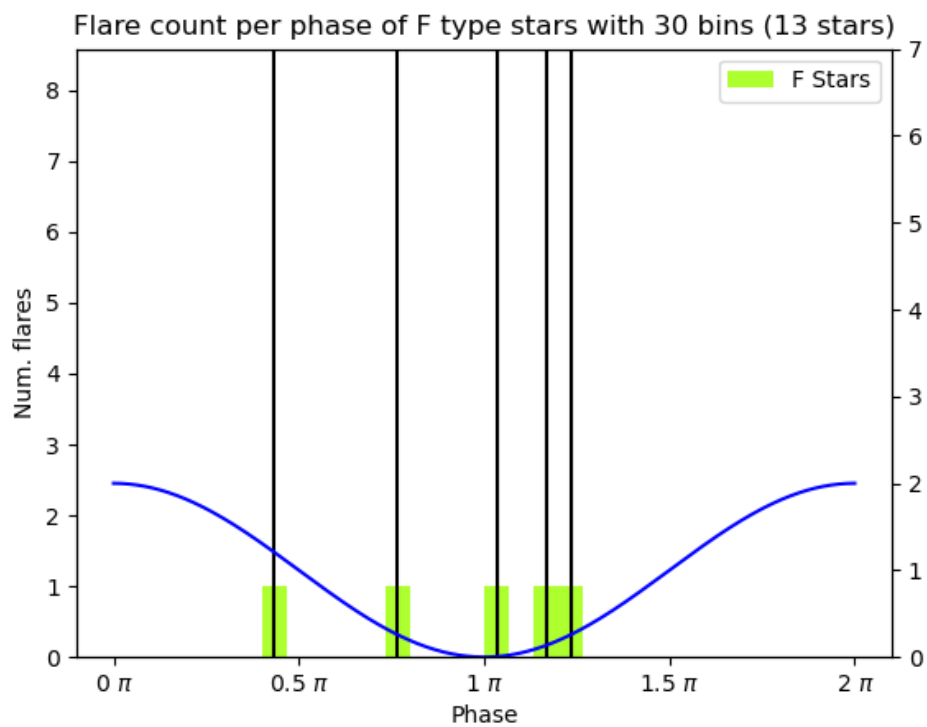


Fig. 4.12.: Histogram showing the amount of flares per phase for all 13 F dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

4.5 Combined results

The results for all 265 stars in the study are shown in this chapter. This includes the stars from tables A.1 to A.4. 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 at phase 0.5π which was present in the histogram for the M type stars (see figure 4.1 in section 4.1) propagates and causes the dip to be 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. Due to the large number of overall flares, the errorbars are small and the errorbars of the peak in the center at phase 1π does not overlap with the other errorbars.

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 with the dip around phase 0.5π and 1.4π . Additionally the peaks from the data of K (figure 4.8) and G (figure 4.10) type stars cause a wider peak at around phase 1π . Additionally there are also smaller, especially less wide peaks at around phases 0.4π , 0.7π and 1.5π .

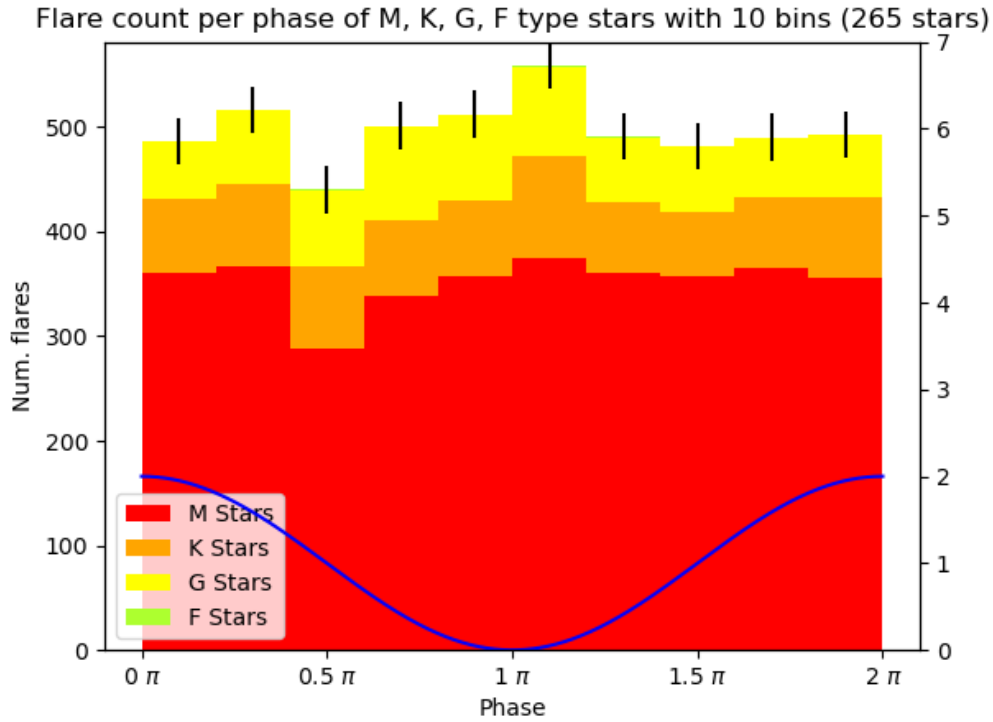


Fig. 4.13.: Histogram showing the amount of flares per phase for all 265 dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins of the phase, showing the number of flares per bin. The colors show the individual amount for each spectral type with the amount being stacked ontop of each other. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and the minimum at phase 1π .

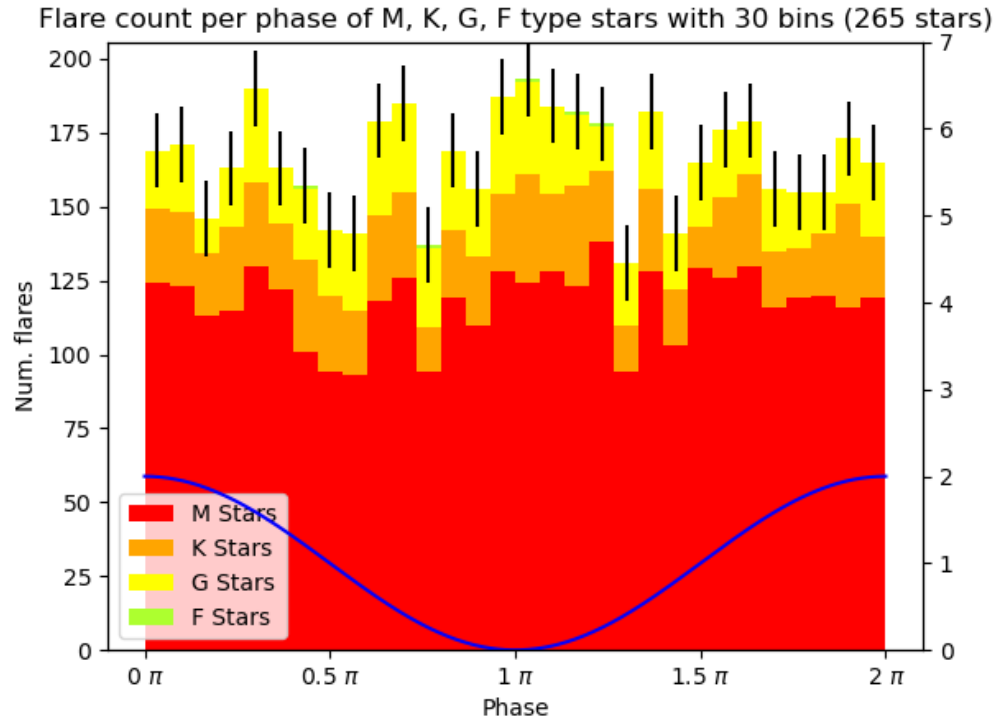


Fig. 4.14.: Histogram showing the amount of flares per phase for all 265 dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 30 bins of the phase, showing the number of flares per bin. The colors show the individual amount for each spectral type with the amount being stacked on top of each other. The error bar shows the standard deviation for the histogram. The blue line indicates an idealized phase (sine curve), with the maximum at phase $0\pi/2\pi$ and 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 what this study was looking for or because the opposite is the case or were in some other way interesting.

4.6.1 V* V471 Tau

V471 Tau is a post-common envelope binary system consisting of a K2 type dwarf and a white dwarf (Muirhead et al. (2022)). The K2 dwarf has a always present dominant spot, which faces the white dwarf (Kóvári et al. (2021)). Figures 4.15 and 4.16 show the histograms of 5 TESS folded lightcurves for V471 Tau with 10 and 30 bins respectively. The TESS lightcurves used are of sectors 42, 43, 44, 70 and 71. The lightcurve of K2 target table ID 80 was rejected by the algorithm. Due to the lightcurve spanning 90 days, and the variability in spots, the folding and fitting algorithm could not produce a reliable output. The blue lines show the used fits for the individual folded lightcurves. In the first figure, there appear two different peaks. The first being at phase 0.5π , and the second one at phase 1.1π . These bins are significantly higher than the surrounding bins with 13/15 flares respectively compared to 1 to 8 on the other bins.

As seen in figures 4.17, 4.18 and 4.19 the transit of the white dwarf occurs at around phase 0 (in these figures) which translates to phase 1π in the normalized phase. Increasing the bins to 30 (figure 4.16) does not change the result much. Due to the individual flare count being lower per bin compared to the previous figure, the errorbars increase in size comparatively. There are still peaks at around 0.5π and 1π .

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.

Figure 4.20 shows the normalized phase and peak of each flare in the data during which part of the phase it happened. It shows that the largest flares happened at around phase 0.5π , 1π and 1.5π . The phase in which the white dwarf transit happens is at around phase 1π .

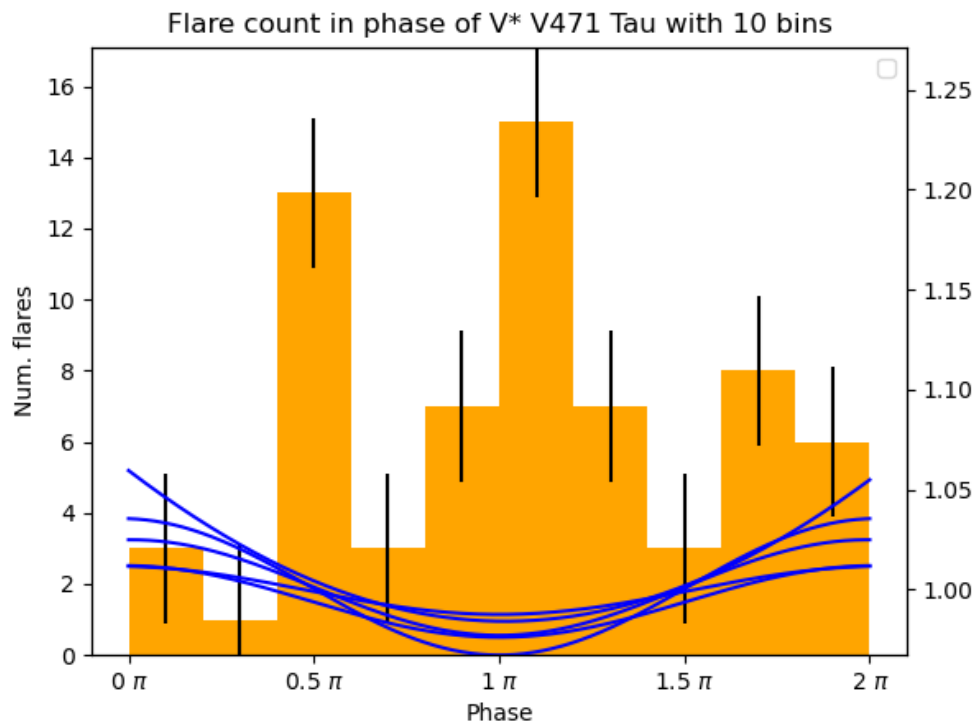


Fig. 4.15.: Histogram of V471 Tau with 10 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

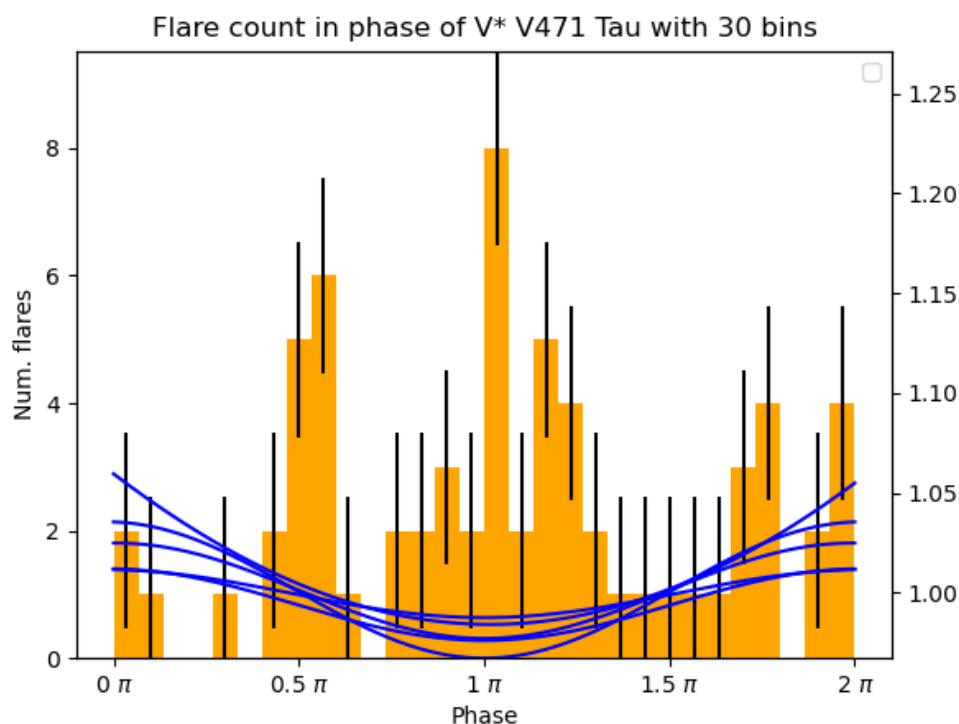


Fig. 4.16.: Histogram of V471 Tau with 30 bins across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with phase minimum at 1π and phase maximum at $0\pi/2\pi$.

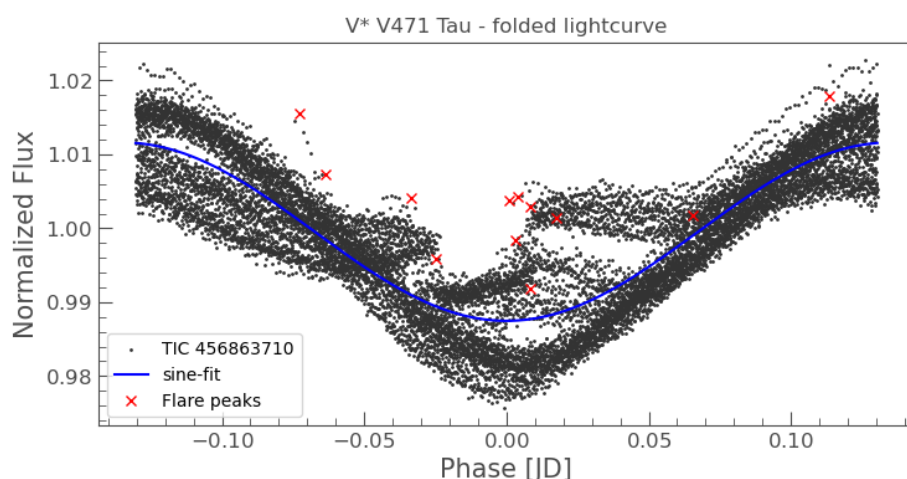


Fig. 4.17.: Folded lightcurve for V* V471 Tau and TESS Sector 42. The blue line shows the sine fit calculated. The red crosses indicate the detected flare peaks.

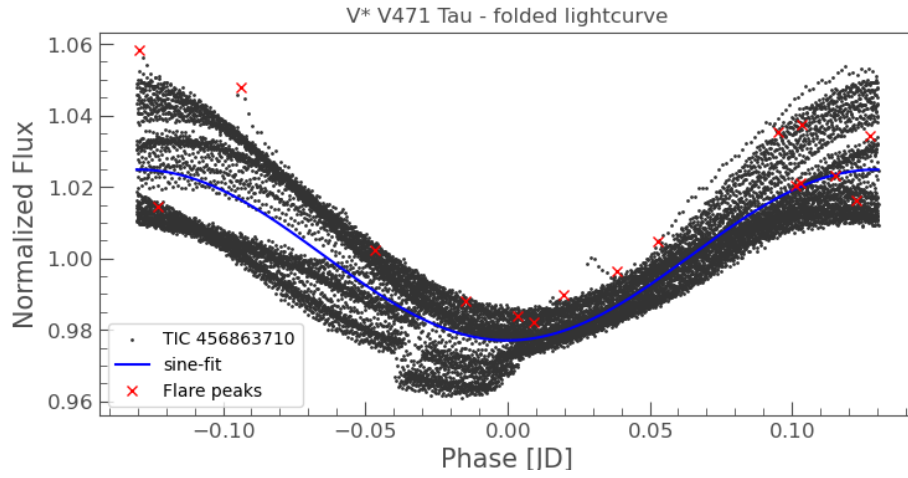


Fig. 4.18.: Folded lightcurve for V* V471 Tau and TESS Sector 43. The blue line shows the sine fit calculated. The red crosses indicate the detected flare peaks.

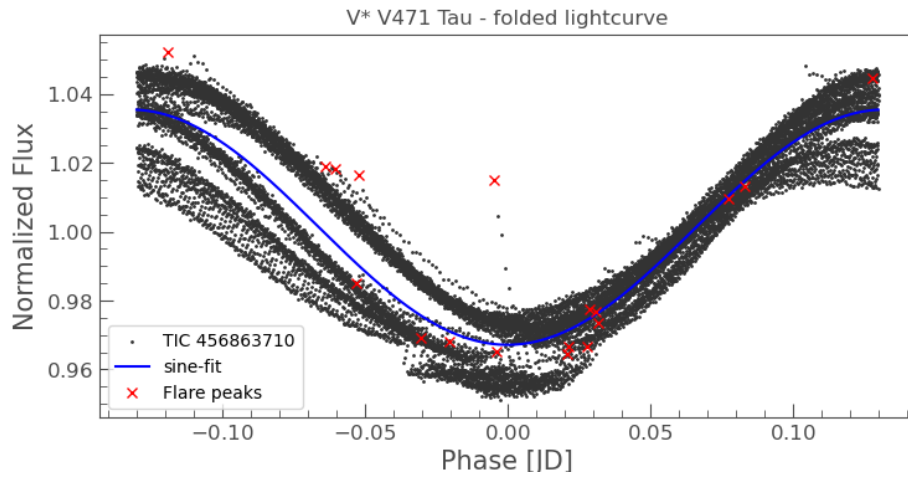


Fig. 4.19.: Folded lightcurve for V* V471 Tau and TESS Sector 44. The blue line shows the sine fit calculated. The red crosses indicate the detected flare peaks.

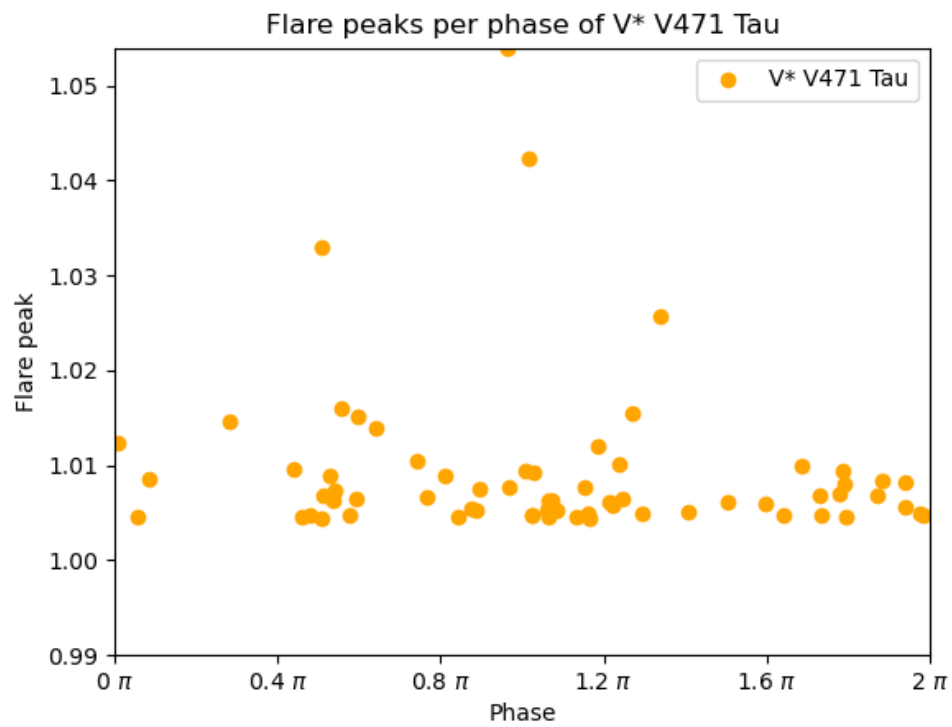


Fig. 4.20.: Distribution of flare peaks in relation to the normalized phase at which they occurred. Y-Axis shows the flare peak and is limited to the value of the highest peak detected. The x-axis shows the normalized phase.

Discussion

5

Conclusion and Outlook

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List of stars

Table A.1.: Table containing all stars used in this study of spectral type M. The first column (Main Identifier) is matched with SIMBADs "MAIN_ID" value for the star. The second column specifies the spectral type of the star according to SIMBAD (with the exception of the stars mentioned in section 3.3, which use the method described in that section). The TIC and KIC columns represent the TESS and Kepler Input Catalogues respectively. The list is sorted first by spectral type, and then by main identifier.

Main Identifier	Spectral Type	TIC	KIC
2MASS J18460555+4332131	M	TIC 123317330	KIC 7800087
2MASS J18472701+4348011	M	TIC 123410529	KIC 8007234
2MASS J18491356+4619042	M	TIC 123447780	KIC 9631548
2MASS J18511354+4227227	M	TIC 164411695	KIC 6925256
2MASS J18511902+4837594	M	TIC 48216443	KIC 11069034
2MASS J18512069+4846013	M	TIC 48216303	KIC 11122350
2MASS J18524238+4828368	M	TIC 48304549	KIC 10960823
2MASS J18525314+4818044	M	TIC 48304703	KIC 10905192
2MASS J18525455+4634012	M	TIC 164457389	KIC 9754582
2MASS J18531060+4050093	M	TIC 237158804	KIC 5597695
2MASS J18535987+4741070	M	TIC 164525174	KIC 10452840
2MASS J18541728+4305206	M	TIC 164529739	KIC 7422811
2MASS J18545269+4107528	M	TIC 350987684	KIC 5855808
2MASS J18561787+4457391	M	TIC 164670879	KIC 8737443
2MASS J18565158+4448162	M	TIC 164671055	KIC 8673358
2MASS J18570619+4516101	M	TIC 164677934	KIC 8935942
2MASS J18572876+4035369	M	TIC 120251682	KIC 5342558
2MASS J18574689+4115593	M	TIC 120254207	KIC 5941226
2MASS J18592859+4351465	M	TIC 164786997	KIC 8012943
2MASS J19000393+4109460	M	TIC 120419969	KIC 5858361
2MASS J19001025+4045358	M	TIC 120422710	KIC 5515142
2MASS J19005916+4400190	M	TIC 164889286	KIC 8150479
2MASS J19011064+4206175	M	TIC 164886887	KIC 6672948
2MASS J19011256+4152067	M	TIC 399822429	KIC 6425989
2MASS J19020142+4110533	M	TIC 120576193	KIC 5859365
2MASS J19023480+4539052	M	TIC 352013620	KIC 9205855

Main Identifier	Spectral Type	TIC	KIC
2MASS J19024516+4429007	M	TIC 352012319	KIC 8417053
2MASS J19030585+4046008	M	TIC 120579026	KIC 5516671
2MASS J19033576+3941263	M	TIC 120684614	KIC 4544623
2MASS J19034709+4317208	M	TIC 158166384	KIC 7592133
2MASS J19035284+4338273	M	TIC 158165866	KIC 7877209
2MASS J19041026+4530403	M	TIC 158172860	KIC 9142714
2MASS J19053703+4235308	M	TIC 158218091	KIC 7018323
2MASS J19061507+5029221	M	TIC 399825094	KIC 12004872
2MASS J19061662+4502422	M	TIC 158274889	KIC 8807085
2MASS J19063685+4928043	M	TIC 399825963	KIC 11498106
2MASS J19064350+5020087	M	TIC 399825217	KIC 11955208
2MASS J19064648+4931162	M	TIC 399825921	KIC 11550428
2MASS J19074075+3752413	M	TIC 121022434	KIC 2557669
2MASS J19081745+3902346	M	TIC 121085753	KIC 3940372
2MASS J19083962+4221137	M	TIC 158388172	KIC 6849112
2MASS J19085407+4320395	M	TIC 158423632	KIC 7670700
2MASS J19103260+4322147	M	TIC 158551504	KIC 7671594
2MASS J19104382+4039368	M	TIC 121329525	KIC 5435958
2MASS J19110814+4024571	M	TIC 121333779	KIC 5262561
2MASS J19114749+4048205	M	TIC 121461193	KIC 5608002
2MASS J19130891+5127421	M	TIC 298961665	KIC 12505054
2MASS J19135561+4319299	M	TIC 158725435	KIC 7673428
2MASS J19141052+4559479	M	TIC 158787568	KIC 9396972
2MASS J19143720+4243450	M	TIC 158795349	KIC 7190459
2MASS J19152845+5001374	M	TIC 299088298	KIC 11808734
2MASS J19160242+4726491	M	TIC 158983853	KIC 10332732
2MASS J19170322+4953087	M	TIC 299159305	KIC 11708034
2MASS J19200001+3844383	M	TIC 122225323	KIC 3640527
2MASS J19200978+4954168	M	TIC 267747418	KIC 11760021
2MASS J19205088+5018194	M	TIC 406950619	KIC 11961075
2MASS J19210354+4523201	M	TIC 159303166	KIC 9017693
2MASS J19213187+4459115	M	TIC 159387244	KIC 8749769
2MASS J19230963+3739397	M	TIC 122672447	KIC 2300039
2MASS J19232149+5107053	M	TIC 417655942	KIC 12356051
2MASS J19233077+5035350	M	TIC 417656504	KIC 12060710
2MASS J19233788+4518061	M	TIC 159520226	KIC 9019435
2MASS J19240851+3747169	M	TIC 122781970	KIC 2441562
2MASS J19242752+5106364	M	TIC 350738203	KIC 12356489
2MASS J19255059+4532219	M	TIC 159761686	KIC 9153754
2MASS J19291103+4821243	M	TIC 424864617	KIC 10921009

Main Identifier	Spectral Type	TIC	KIC
2MASS J19304396+4112528	M	TIC 137759349	KIC 5962956
2MASS J19304840+4142454	M	TIC 137758161	KIC 6366739
2MASS J19335656+4010546	M	-	KIC 5016904
2MASS J19343395+4137235	M	TIC 138222062	KIC 6290811
2MASS J19353467+3943573	M	TIC 138436033	KIC 4662431
2MASS J19353874+4708324	M	TIC 270790828	KIC 10146539
2MASS J19365745+4628121	M	TIC 270957843	KIC 9716117
2MASS J19374745+4341098	M	TIC 271047224	KIC 7898781
2MASS J19421615+4928069	M	TIC 27531488	KIC 11515276
2MASS J19423900+5108356	M	TIC 27639064	KIC 12365719
2MASS J19433653+4758149	M	TIC 27645448	KIC 10676126
2MASS J19443380+4843497	M	TIC 27770198	KIC 11147271
2MASS J19444493+4720327	M	TIC 272279258	KIC 10285642
2MASS J19450930+4754591	M	TIC 27771932	KIC 10677397
2MASS J19451164+4345265	M	TIC 272270363	KIC 7973675
2MASS J19454134+3906345	M	TIC 184471264	KIC 4077867
2MASS J19471875+4123248	M	TIC 239228371	KIC 6060845
2MASS J19471987+4747258	M	TIC 272841049	KIC 10548508
2MASS J19480997+4310160	M	TIC 272943707	KIC 7547969
2MASS J19503771+4705359	M	TIC 273378083	KIC 10091786
2MASS J19503804+4041450	M	TIC 169816129	KIC 5471468
2MASS J19505785+4630250	M	TIC 273379615	KIC 9786877
2MASS J19510637+4505045	M	TIC 273383619	KIC 8836388
2MASS J19525571+4743328	M	TIC 273874034	KIC 10553513
2MASS J19542833+4420425	M	TIC 268158580	KIC 8387621
2MASS J19543981+4814406	M	TIC 264508845	KIC 10880514
2MASS J19550625+4009192	M	TIC 171101426	KIC 5041192
2MASS J19553603+4805356	M	TIC 416528859	KIC 10753072
2MASS J19561258+4335485	M	TIC 268485803	KIC 7847566
2MASS J19584764+4711122	M	TIC 269029909	KIC 10165815
2MASS J20000387+4531405	M	TIC 239234887	KIC 9179906
ATO J285.1153+45.7850	M	TIC 164882037	KIC 9267818
KOI-1654	M	TIC 48355200	KIC 11546211
UCAC4 639-062929	M	TIC 120963868	KIC 2284919
UCAC4 643-073385	M	TIC 138647610	KIC 3454793
UCAC4 651-066418	M	TIC 120354289	KIC 4904647
UCAC4 661-082974	M	TIC 268288304	KIC 6720765
UCAC4 664-071715	M	TIC 158430593	KIC 7104739
UCAC4 668-073165	M	TIC 158432884	KIC 7741987
UCAC4 683-066189	M	TIC 351897570	KIC 9692206

Main Identifier	Spectral Type	TIC	KIC
UCAC4 707-062317	M	TIC 299097784	KIC 12403318
1RXS J060224.9-163451	M0	TIC 95328477	-
V* MY Tau	M0.5e	TIC 348638763	-
WOH S 209	M0:	TIC 179038379	-
Kepler-210	M0V	TIC 63283780	KIC 7447200
MCC 428	M0V	TIC 434136638	-
V* HK Aqr	M0Ve	TIC 5656273	-
HG 7-26	M1	TIC 345454031	-
V* OT Ser	M1.0V	TIC 355793860	-
V* V631 Tau	M1.5	TIC 348638813	-
2MASS J18563342+4513481	M1.5V	TIC 164670606	KIC 8935655
G 6-33	M1.5V	TIC 434160946	-
V* FF And	M1Ve+M1Ve	TIC 267802440	-
HD 197481	M1VeBa1	TIC 441420236	-
[LM84] 3-13	M2	TIC 165124012	-
V* AX Cnc	M2.0	TIC 175233993	-
2MASS J19412234+5104273	M2.1	TIC 27454242	KIC 12314646
1RXS J004211.1-425245	M2.2	TIC 80427281	-
2MASS J04133314-5231586	M2.4	TIC 219229275	-
PM J19399+3950	M2.5	TIC 138893136	KIC 4758595
UCAC4 647-065171	M2.5	TIC 121215155	KIC 4142890
G 10-29	M2.5V	TIC 396951485	-
LP 474-124	M2.5V	TIC 348663808	-
2MASS J19130537+5020559	M2.5Ve	TIC 298962893	KIC 11957647
ASAS J232857-6802.4	M2.5Ve	TIC 229807000	-
2MASS J19324802+4200580	M2.7	TIC 275496670	KIC 6610837
2MASS J19445931+4812415	M2.8	TIC 27772498	KIC 10872868
V* V497 Tau	M2.9	TIC 258032026	-
CD-51 13128	M2Ve	TIC 140045538	-
2MASS J19183060+4153031	M3	TIC 122067236	KIC 6436291
[PS78] 219	M3+	TIC 11652986	-
UCAC4 698-065839	M3.0	TIC 48504458	KIC 11495571
G 9-11	M3.0V	TIC 21246336	-
UCAC4 673-078334	M3.0Ve	TIC 272272592	KIC 8507979
G 209-3	M3.4	TIC 28231379	KIC 10877432
V* LT Tau	M3.5	TIC 258067389	-
BD-15 6290	M3.5V	TIC 188580272	-
LP 426-35	M3.5V	TIC 197247983	-
LP 737-14	M3.5V	TIC 335628483	-
2MASS J22371494-2622332	M3.5Ve	TIC 326446019	-

Main Identifier	Spectral Type	TIC	KIC
BD+16 2708	M3V	TIC 258105174	-
KOI-256	M3V	TIC 48528261	KIC 11548140
LAMOST J192817.82+410412.2	M3V	TIC 137410897	KIC 5791720
2MASS J18535530+4310389	M3Ve	TIC 164529625	KIC 7505644
2MASS J18592696+4548446	M3Ve	TIC 164784762	KIC 9328653
2MASS J19015564+4134218	M3Ve	TIC 120576760	KIC 6187812
CD-43 9546	M3Ve	TIC 334524122	-
CD-56 1032A	M3Ve	TIC 220433363	-
2MASS J04534379-5836247	M3e	TIC 220432563	-
2MASS J22534969-1721358	M4	TIC 188586529	-
LP 873-37	M4	TIC 99566892	-
1RXS J185504.7+425952	M4.0V	TIC 164644375	KIC 7341653
HG 8-80	M4.0V	TIC 435916078	-
V* EV Lac	M4.0Ve	TIC 154101678	-
2MASS J01275875-6032243	M4.2	TIC 237910557	-
2MASS J19150930+5101139	M4.5V	TIC 299089441	KIC 12302994
2MASS J19573917+4554182	M4.5V	TIC 268711231	KIC 9426508
G 6-7	M4.5V	TIC 456938518	-
UCAC4 683-069625	M4.5V	TIC 159171299	KIC 9705079
2MASS J18432784+4727325	M4Ve	TIC 123205792	KIC 10318386
2MASS J18474286+4218039	M4Ve	TIC 123408865	KIC 6837702
2MASS J18535193+4327449	M4Ve	TIC 164529313	KIC 7734382
2MASS J19005766+4428279	M4Ve	TIC 164889852	KIC 8416220
2MASS J19045588+3738361	M4Ve	TIC 120825083	KIC 2283749
CD-56 1032B	M4Ve	TIC 220433364	-
Kepler-1646	M4Ve	TIC 158552258	KIC 7350067
2MASS J21484123-4736506	M5	TIC 147421845	-
UCAC3 53-724	M5.5V	TIC 425937691	-
G 205-40	M5V	TIC 164458193	KIC 9201463
LP 357-206	M5e	TIC 14079970	-
LP 760-3	M6.5V	-	-
2MASS J19202351+5037161	M6Ve	TIC 267746625	KIC 12108566
V* V692 Tau	M:	TIC 149923415	-

Table A.2.: Table containing all stars used in this study of spectral type K. The first column (Main Identifier) is matched with SIMBADs "MAIN_ID" value for the star. The second column specifies the spectral type of the star according to SIMBAD (with the exception of the stars mentioned in section 3.3, which use the method described in that section). The TIC and KIC columns represent the TESS and Kepler Input Catalogues respectively. The list is sorted first by spectral type, and then by main identifier.

Main Identifier	Spectral Type	TIC	KIC
1RXS J064643.6-770027	K	TIC 177255827	-
2MASS J18524052+4156057	K	-	KIC 6500181
2MASS J18534407+4208274	K	-	KIC 6668646
2MASS J18535462+4135227	K	-	KIC 6183672
2MASS J19004200+3903124	K	TIC 399794444	KIC 3935803
2MASS J19082791+4337114	K	TIC 158389986	KIC 7879384
2MASS J19324909+4229041	K	TIC 275495685	KIC 6953069
2MASS J19404949+5046469	K	TIC 27398219	KIC 12166457
ATO J296.1841+42.6311	K	TIC 272184059	KIC 7133807
CPD-19 878	K	TIC 93125144	-
KOI-7449	K	TIC 279918401	KIC 11495989
KOI-8047	K	TIC 290034561	KIC 11294822
Kepler-1259	K	TIC 273592350	KIC 10028535
Kepler-1782	K	TIC 123202646	KIC 8142942
Kepler-1856	K	TIC 27687265	KIC 12469800
Kepler-1966	K	TIC 137627194	KIC 5962262
Kepler-246	K	TIC 272484980	KIC 7134976
Kepler-693	K	TIC 237159318	KIC 5164255
PM J07058-5848	K	TIC 279615427	-
TYC 1360-957-1	K	TIC 247117382	-
HD 245924	K0IV	TIC 19934471	-
2MASS J19200703+4335050	K0V	TIC 159220196	KIC 7816999
BD+41 3306	K0V	TIC 394172596	KIC 6278762
CD-26 1578	K0V	TIC 44797824	-
TYC 553-33-1	K0V:e	TIC 405405298	-
RX J1925.0+4429	K1V	TIC 159721038	KIC 8429280
V* V4371 Sgr	K1V	TIC 151839506	-
HD 215341	K1Ve	TIC 145752454	-
TYC 582-114-1	K1Ve	TIC 344163180	-
V* LQ Hya	K1Vp	TIC 46907042	-
Kepler-1558	K2	TIC 158322085	KIC 10000941
HD 283750	K2.5Ve	TIC 125838647	-
CD-52 381	K2V(e)	TIC 229151691	-

Main Identifier	Spectral Type	TIC	KIC
V* V471 Tau	K2V+DA	TIC 456863710	-
Kepler-411	K3V	TIC 399954349	KIC 11551692
BD-13 6131	K3Ve	TIC 437696706	-
V* BY Dra	K4Ve+K7.5Ve	TIC 47579336	-
2MASS J19400800+4923036	K5	TIC 27390487	KIC 11461764
V* CC Eri	K7V	TIC 142206123	-

Table A.3.: Table containing all stars used in this study of spectral type G. The first column (Main Identifier) is matched with SIMBADs "MAIN_ID" value for the star. The second column specifies the spectral type of the star according to SIMBAD (with the exception of the stars mentioned in section 3.3, which use the method described in that section). The TIC and KIC columns represent the TESS and Kepler Input Catalogues respectively. The list is sorted first by spectral type, and then by main identifier.

Main Identifier	Spectral Type	TIC	KIC
2MASS J18425375+4345336	G	TIC 123198563	KIC 7936748
2MASS J18495232+4309276	G	TIC 123489639	KIC 7503439
2MASS J18525868+4530560	G	TIC 164458315	KIC 9137611
2MASS J18582492+4446498	G	TIC 164779298	KIC 8609289
2MASS J19012927+4104159	G	TIC 120496415	KIC 5773205
2MASS J19043346+4427484	G	TIC 158171605	KIC 8417863
2MASS J19061691+4654395	G	TIC 158272786	KIC 10000509
2MASS J19065549+3937268	G	TIC 121012476	KIC 4546541
2MASS J19080680+4450500	G	TIC 158391683	KIC 8678334
2MASS J19100183+4257041	G	TIC 158552191	KIC 7350021
2MASS J19182441+4439465	G	TIC 159097797	KIC 8554173
2MASS J19184939+4418233	G	TIC 159107064	KIC 8359762
2MASS J19185028+4633324	G	TIC 159171504	KIC 9765670
2MASS J19250540+3734332	G	TIC 137097085	KIC 2159377
2MASS J19280249+3911165	G	TIC 137402956	KIC 4058829
2MASS J19283146+3837123	G	TIC 137484235	KIC 3547283
2MASS J19313155+4628249	G	TIC 63452929	KIC 9712781
2MASS J19320792+3933052	G	TIC 137972488	KIC 4469481
2MASS J19350077+4608423	G	TIC 270698467	KIC 9531002
2MASS J19354814+4118464	G	TIC 138431713	KIC 6049426
2MASS J19354900+4623499	G	TIC 270789534	KIC 9654338
2MASS J19364457+4403341	G	TIC 270859571	KIC 8172597
2MASS J19370439+4626209	G	TIC 270957778	KIC 9716208
2MASS J19390861+4046149	G	TIC 138725759	KIC 5544024

Main Identifier	Spectral Type	TIC	KIC
2MASS J19395042+4622296	G	TIC 271354512	KIC 9657062
2MASS J19415575+4522369	G	TIC 271664690	KIC 9032578
2MASS J19450785+5108395	G	TIC 27778260	KIC 12367153
2MASS J19484658+5002007	G	TIC 28084005	KIC 11825619
2MASS J19491761+4638356	G	TIC 273131067	KIC 9845711
2MASS J19535154+4211197	G	TIC 274119294	KIC 6719122
2MASS J19551628+4145582	G	TIC 171093514	KIC 6390935
2MASS J19553242+4737586	G	TIC 268382866	KIC 10491422
2MASS J19562459+4408276	G	TIC 268606798	KIC 8257716
2MASS J19572618+4520510	G	TIC 268712881	KIC 9048032
2MASS J19583564+4352320	G	TIC 269121724	KIC 8055957
2MASS J20060991+4417004	G	TIC 185335830	KIC 8332459
ATO J285.5682+44.5725	G	TIC 352012409	KIC 8481574
BD-08 995	G	TIC 43472154	-
KOI-1747	G	TIC 159717069	KIC 7032421
KOI-2324	G	TIC 159105557	KIC 7746958
KOI-5796	G	TIC 63070665	KIC 10470779
KOI-5810	G	TIC 123494489	KIC 10581308
KOI-5825	G	TIC 27183790	KIC 10737437
KOI-5952	G	TIC 27845077	KIC 12071775
KOI-741	G	TIC 272840512	KIC 10418797
Kepler-1060	G	TIC 120691237	KIC 4544907
Kepler-1198	G	TIC 158843826	KIC 8681734
Kepler-1839	G	TIC 27082730	KIC 11818607
Kepler-513	G	TIC 48503953	KIC 11802615
Kepler-725	G	TIC 164652841	KIC 8672910
Kepler-739	G	TIC 159225155	KIC 9766437
TYC 4595-107-1	G	TIC 394030788	-
UCAC4 640-067417	G	TIC 122517231	KIC 2709412
UCAC4 686-075120	G	TIC 269030397	KIC 10098932
V* V452 Lyr	G	-	KIC 7742289
BD-01 2318	G0	TIC 78234015	-
HD 295290	G0	TIC 53417036	-
TYC 3560-458-1	G0	TIC 26815845	KIC 10922836
TYC 3557-1509-1	G0.5V	TIC 273379797	KIC 9726613
TYC 3139-951-1	G0V	TIC 138215507	KIC 4660797
Kepler-1424	G1.5Vb	TIC 122706631	KIC 5096590
KOI-6202	G1V	TIC 164669854	KIC 9389245
Kepler-400	G2V	TIC 122707140	KIC 5272233
TYC 3131-2137-1	G2V	TIC 164460243	KIC 7871914

Main Identifier	Spectral Type	TIC	KIC
TYC 3146-672-1	G2V	TIC 159448893	KIC 7523785
TYC 3545-2661-1	G2V	TIC 399827121	KIC 10850420
HD 183473	G5	TIC 63120335	KIC 7201012
HD 214261	G5	TIC 200501090	-
KOI-644	G5	TIC 122138452	KIC 5356593
TYC 3550-241-1	G5	TIC 299088815	KIC 12008308
HD 23524	G5V	TIC 428761512	-
TYC 3562-2088-1	G5V	TIC 273872314	KIC 10093680
V* AG Lep	G5V	TIC 92845906	-
HD 222259A	G6V	TIC 410214986	-
Kepler-605	G7	TIC 158423850	KIC 7595157
TYC 3128-2312-1	G8V	TIC 120686876	KIC 5944209
HD 180445	G8V(e)	TIC 97914505	-
HD 220186	G9Ve	TIC 49619607	-

Table A.4.: Table containing all stars used in this study of spectral type F. The first column (Main Identifier) is matched with SIMBADs "MAIN_ID" value for the star. The second column specifies the spectral type of the star according to SIMBAD (with the exception of the stars mentioned in section 3.3, which use the method described in that section). The TIC and KIC columns represent the TESS and Kepler Input Catalogues respectively. The list is sorted first by spectral type, and then by main identifier.

Main Identifier	Spectral Type	TIC	KIC
2MASS J18491671+4410445	F	TIC 123449867	KIC 8212826
KOI-4698	F	TIC 159643077	KIC 10663738
Kepler-1271	F	TIC 120825510	KIC 1996180
Kepler-1443	F	TIC 164525743	KIC 10057494
Kepler-380	F	TIC 48132154	KIC 11121752
Kepler-494	F	TIC 169176556	KIC 6305192
TYC 3134-301-1	F	TIC 137483286	KIC 3852772
KOI-19	F3/F5V	TIC 123201406	KIC 7255336
TYC 3557-727-1	F3/F5V	TIC 273684688	KIC 9788113
TYC 3140-1658-1	F5	TIC 138967825	KIC 5802601
TYC 3557-1501-1	F6IV	TIC 273043859	KIC 9724820
KOI-44	F7IV	TIC 239276046	KIC 8845026
Kepler-1084	F8V	TIC 267749737	KIC 10857519

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 / Mod- ule	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.

```
1 import sys , os , math
2 import numpy as np
3 import pylab as pl
4
5 # here we have a comment on the scripting
6
7 for iii in np.arange(0,42):
8     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

```

1 &star_job
2     show_log_description_at_start = .true.
3     pgstar_flag = .true.
4 / ! end of star_job namelist
5
6 &controls
7     extra_terminal_output_file = 'log1'
8     log_directory = 'LOGS1'
9 / ! end of controls namelist
10
11 &pgstar
12     History_Panels1_win_flag = .true.
13     History_Panels1_win_width = 5
14     History_Panels1_win_aspect_ratio = 1.0
15
16     History_Panels1_title = 'Orbital_evolution'
17     History_Panels1_num_panels = 2
18
19     History_Panels1_yaxis_name(1) = 'period_days'
20     History_Panels1_other_yaxis_name(1) =
21     'lg_mstar_dot_1'
22     History_Panels1_yaxis_name(2) = 'Jdot'
23     History_Panels1_other_yaxis_name(2) =
24     'binary_separation'
25 / ! end of pgstar namelist

```

Listing B.3: inlist2

```

1 &star_job
2     show_log_description_at_start = .false.
3
4 / ! end of star_job namelist
5
6 &controls
7     extra_terminal_output_file = 'log2'
8     log_directory = 'LOGS2'
9 / ! end of controls namelist
10
11 &pgstar
12
13
14
15
16
17
18
19
20
21
22
23
24
25 / ! end of pgstar namelist

```

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

```

1  ! inlist to evolve a 15 solar mass star
2
3  ! For the sake of future readers of this file ,
4  ! ONLY include the controls you are actually using.
5  ! DO NOT include all of the other controls that
6  ! simply have their default values.
7
8  &star_job
9
10 ! begin with a pre-main sequence model
11   create_pre_main_sequence_model = .true.
12
13 ! save a model at the end of the run
14   save_model_when_terminate = .false.
15   save_model_filename = '15M_at_TAMS.mod'
16
17 ! display on-screen plots
18   pgstar_flag = .true.
19
20 / !end of star_job namelist
21
22
23 &controls
24
25 ! starting specifications
26   initial_mass = 15 ! in Msun units
27
28 ! options for energy conservation
29   use_dedt_form_of_energy_eqn = .true.
30   use_gold_tolerances = .true.
31
32 ! stop when the star nears ZAMS (Lnuc/L > 0.99)
33   Lnuc_div_L_zams_limit = 0.99d0
34   stop_near_zams = .true.
35
36 ! stop when the center mass fraction
37 of h1 drops below this limit
38   xa_central_lower_limit_species(1) = 'h1'
39   xa_central_lower_limit(1) = 1d-3
40
41 / ! end of controls namelist
42
43 &pgstar
44
45 ! MESA uses PGPLOT for live plotting and
46 ! gives the user a tremendous amount of control
47 ! of the presentation of the information.
48

```

```
49 ! show HR diagram
50 ! this plots the history of L,Teff over many
51 ! timesteps
52   HR_win_flag = .true.
53
54 ! set static plot bounds
55   HR_logT_min = 3.5
56   HR_logT_max = 4.6
57   HR_logL_min = 2.0
58   HR_logL_max = 6.0
59
60 ! set window size (aspect_ratio = height/width)
61   HR_win_width = 6
62   HR_win_aspect_ratio = 1.0
63
64
```

```
65 ! show temperature/density profile
66 ! this plots the internal structure at single
67 ! timestep
68   TRho_Profile_win_flag = .true.
69
70 ! add legend explaining colors
71   show_TRho_Profile_legend = .true.
72
73 ! display numerical info about the star
74   show_TRho_Profile_text_info = .true.
75
76 ! set window size (aspect_ratio = height/width)
77   TRho_Profile_win_width = 8
78   TRho_Profile_win_aspect_ratio = 0.75
79
80 / ! 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 recommended¹ by the *Zentrum für Lehrkompetenz (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 $\text{\LaTeX}$ 2 ϵ . 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 18, 2025

Markus Ornik