

Relating spot and flare/superflare occurrence on dwarf stars

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May 25, 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

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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 25, 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

This chapter gives an introduction to the goals of this study. It also gives a summary of the current knowledge related to this study. Afterwards there will be summaries on topics related to this study, giving explanations on the various spectral types of stars, flares and spots, as well as giving an introduction to the space missions which data was used.

1.1 Goals and current knowledge

The goal of this study is to relate the appearance of flares/superflares to that of star spots on a large sample of stars of various spectral types. This is done by folding the lightcurves and the normalizing the phases. Due to the appearance of spots on the stars surface, the star is slightly dimmed, causing a local minimum in the lightcurve. This dimming can be observed with the Kepler and TESS (Transiting Exoplanet Survey Satellite) space missions. Araújo and Valio (2021) focused on Kepler-411 by investigating the relation between superflares and star spots on that star. They found a positive correlation between the energy of flares and the area of star spots (Araújo and Valio (2021)) on Kepler-411. They then compared their results for Kepler-411, which produced multiple superflares, with Kepler-210, which did not produce superflares while having the same number of spots (Araújo and Valio (2023)). They found the spots on Kepler-210 to be larger, warmer and therefore being magnetically weaker/less complex compared to Kepler-411 and concluded that the area of starspots is not the only relevant parameter for superflare occurrence (Araújo and Valio (2023)).

Doyle et al. (2018) studied 34 M dwarfs from the K2 mission, using short cadence observational data. They confirmed that stars with a rotational period of less than 10 days showed more flares, which was already shown previously (Mohanty and Basri (2003), McLean et al. (2012)). Furthermore they found no star with a preference for when flares occurred during the rotational phase (Doyle et al. (2018)). A similar study using TESS 2 minute cadence data has been conducted by Doyle et al. (2019). In this study they used data of 167 M dwarfs and found a total of 1834 flares. Similar to the study on K2 data, they found no preference for rotational phase (Doyle et al. (2019)).

Another possible cause for a periodic increase in flares is star-planet interaction

(SPI), which is studied by Ilin and Poppenhaeger (2022) for the star AU Mic. While they found a signal in their used TESS lightcurves correlating with the orbital period of AU Mic b, they require more observation time to get a $> 3\sigma$ detection (Ilin and Poppenhaeger (2022)).

Further analysis on periodic flare occurrence was done by Howard and Law (2021), who studied lightcurves of 284 M dwarfs. They found three targets (TIC 80427281, TIC 95328477, TIC 220432563) with a confirmed flare periodicity, which correlates to their rotational period or half of it.

Roettenbacher and Vida (2018) investigated a sample of 119 stars from spectral types M to F. They found that flares which increase the stellar flux by 1% to 5% appear more often while larger starspots are visible, while flares which increase the flux by more than 5% do not seem to have this dependency (Roettenbacher and Vida (2018)).

1.2 Spectral Types

1.3 Flares and Starspots

1.4 Space missions

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),

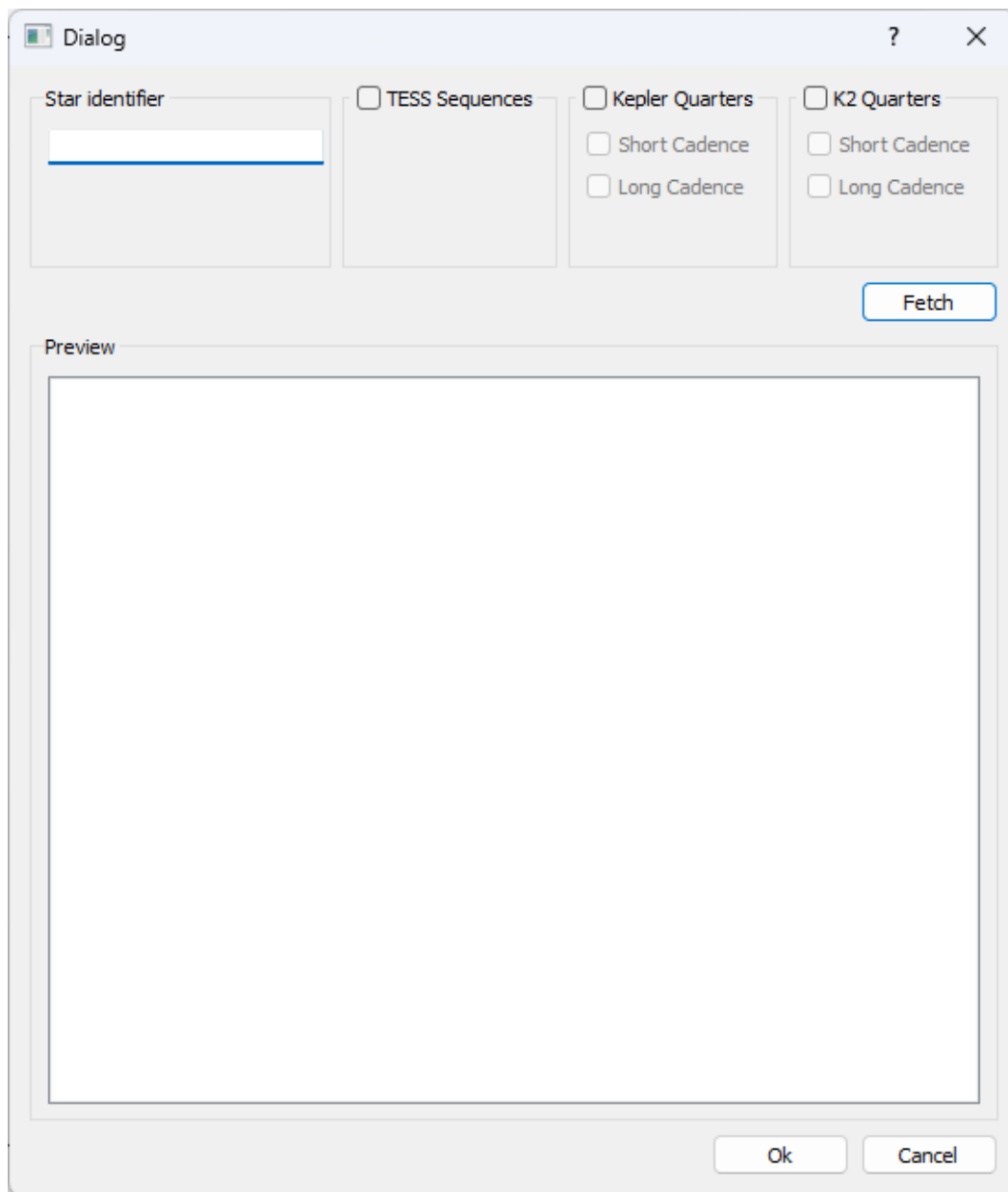


Fig. 2.1.: GUI window for downloading new fit files with astroquery designed using the Qt5 designer shipped with PyQt5 (Riverbank Computing Limited (2025)). The star identifier field supports one or more (separated by a semicolon) identifiers. There are checkboxes to select TESS, Kepler (long and/or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

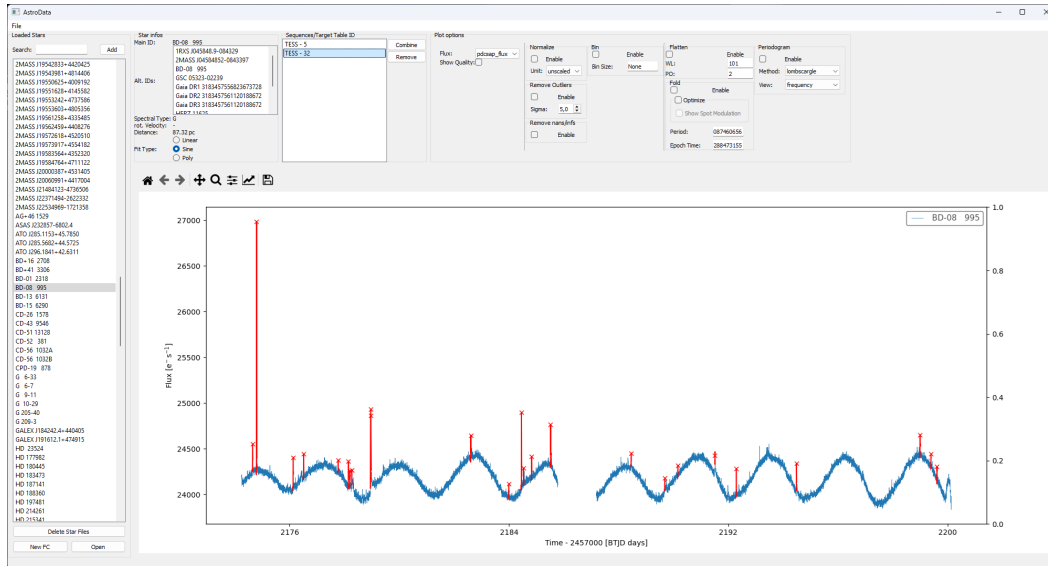


Fig. 2.2.: Main GUI window. This window was designed with the Qt5 designer shipped with PyQz5 (Riverbank Computing Limited (2025)). It shows a list of all available stars with their main identifier (taken from SIMBAD (Wenger et al. (2000))) sorted alphabetically. The "Star infos" box contains additional 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.

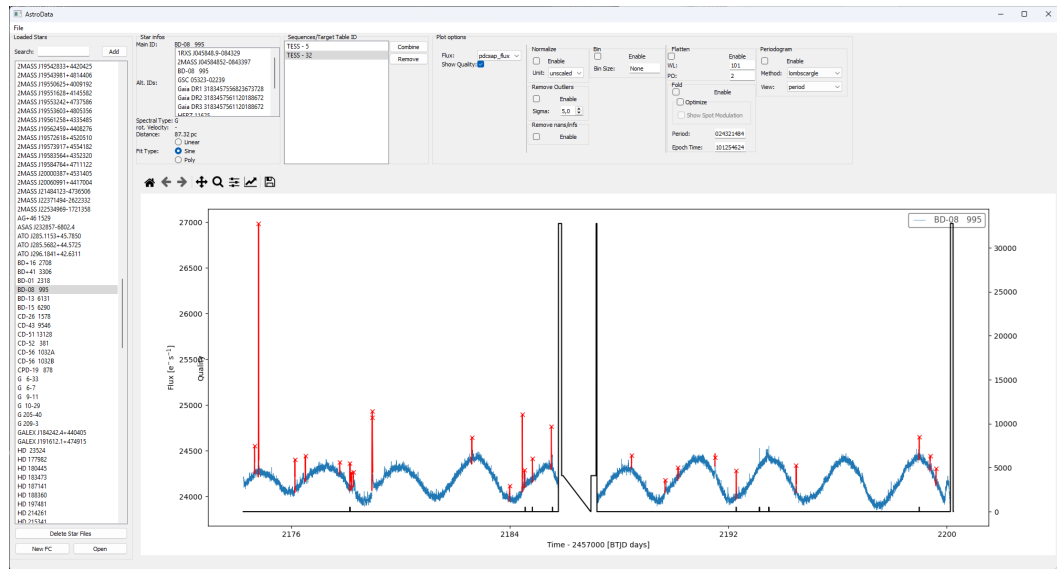


Fig. 2.3.: Main GUI window. Same as in figure 2.2, with the difference that the data quality flag is also shown.

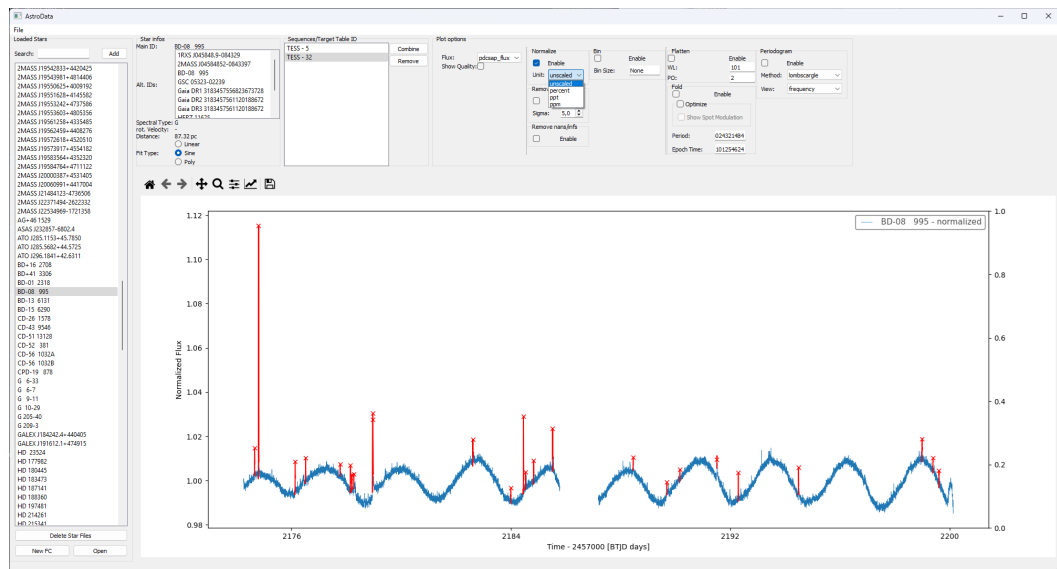


Fig. 2.4.: Main GUI window. Same as in figure 2.2, with the difference that the lightcurve was normalized. It also shows all possible normalize options the lightcurve python package (Lightcurve Collaboration et al. (2018)) supports.

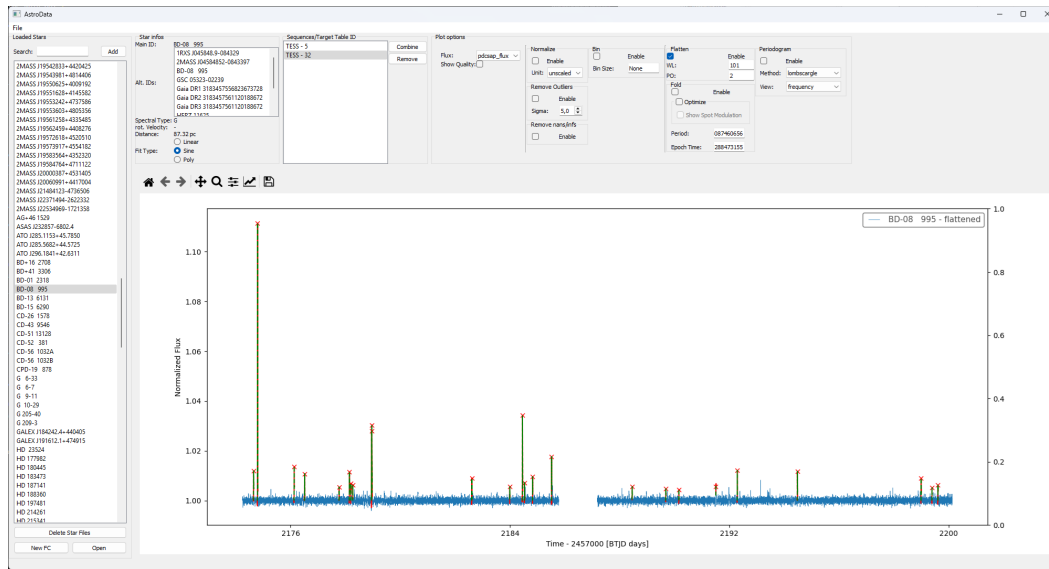


Fig. 2.5.: Main GUI window. Showing the same lightcurve as figure 2.2, with the difference that it is now flattened. The green line shows a fit of the flare. This is described in chapter 3.2.

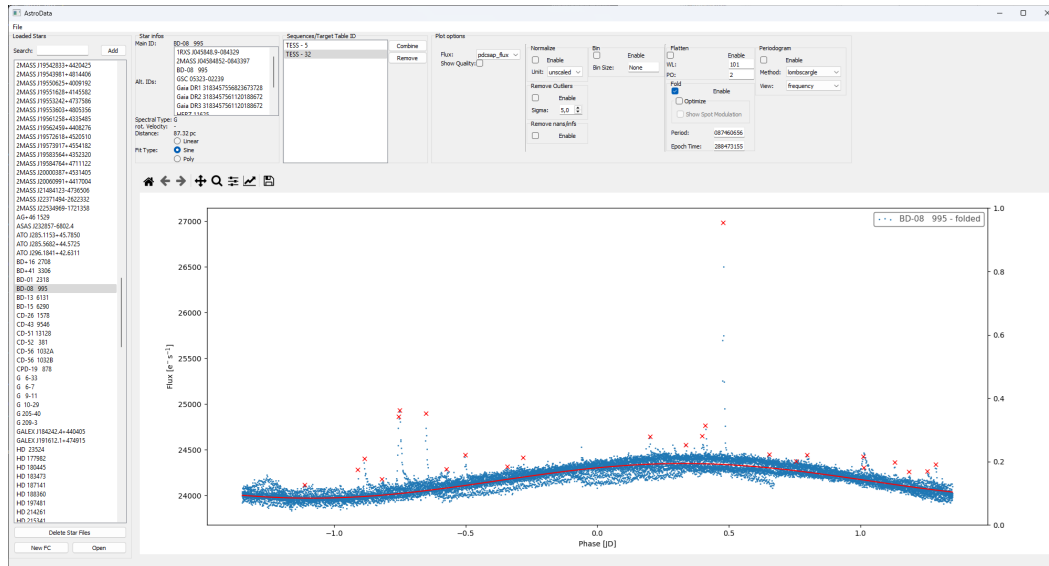


Fig. 2.6.: Main GUI window. Showing the same lightcurve as figure 2.2, with the difference that it is now folded with an period of 2.697 days. Additionally vertical lines are shown which indicate the region around the minima and maxima of the folded lightcurve respectively.

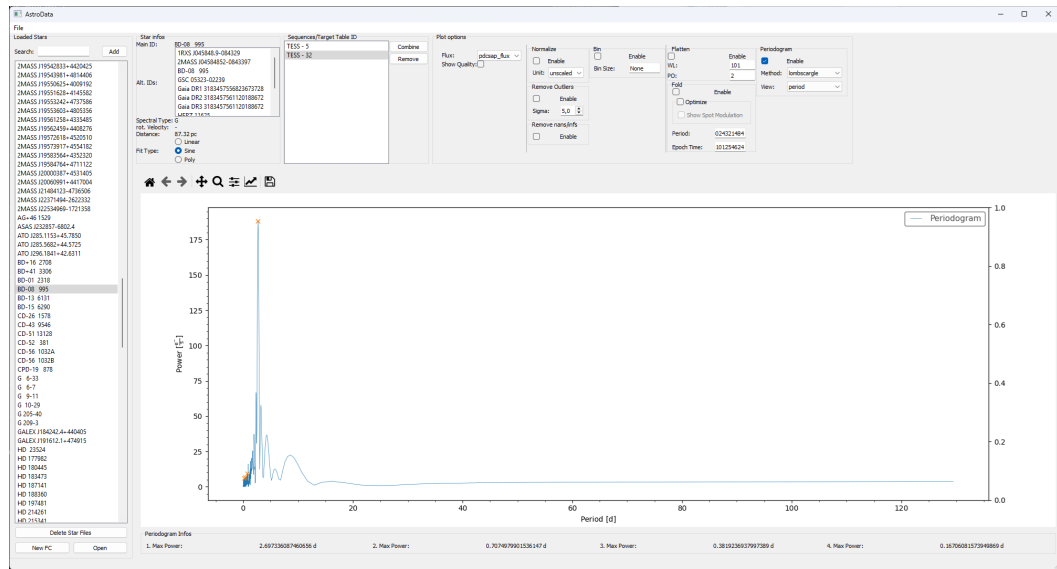


Fig. 2.7.: Main GUI window. Showing the periodogram of the lightcurve in figure 2.2 using the lombscargle algorithm. Furthermore it shows the four highest peaks (which are atleast 100 datapoints separated). The method is explained in chapter 3.2.

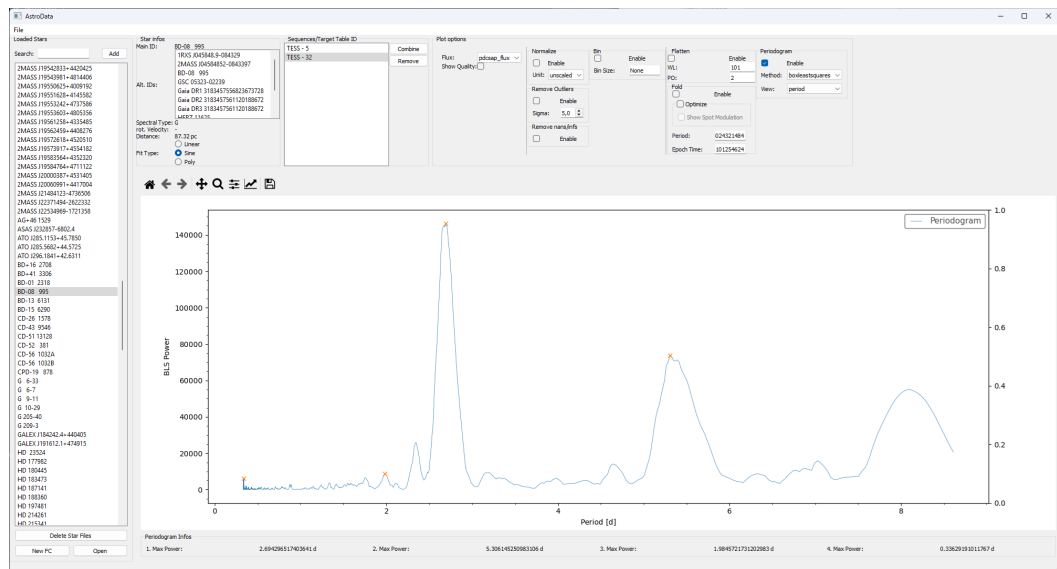


Fig. 2.8.: Main GUI window. Showing the periodogram of the lightcurve in figure 2.2 using the box least square algorithm. Similarly to figure 2.7 the four highest peaks are marked with a red 'x'.

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.

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

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 4.1a and 4.1b show histograms, with 10 and 30 bins respectively, of the amount of flares during the normalized phase.

Looking at figure 4.1a 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 4.1b), 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 4.1a) 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.

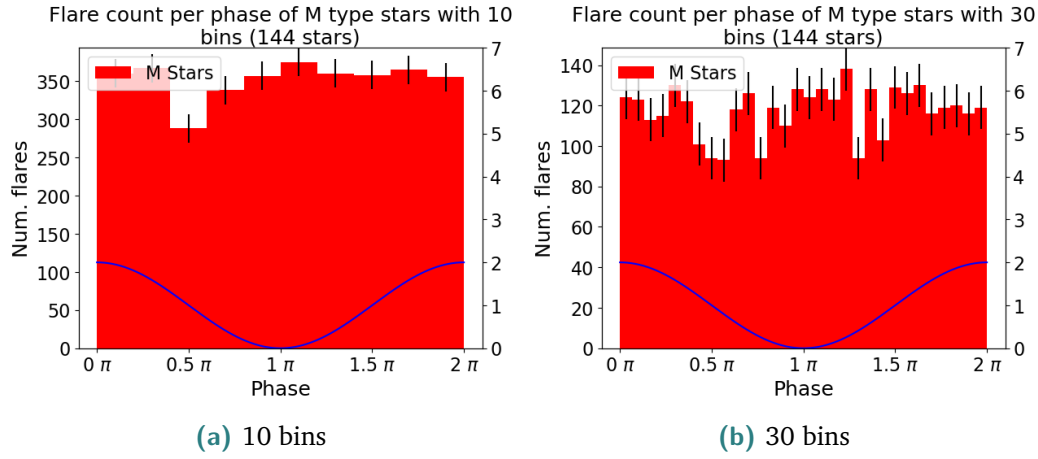


Fig. 4.1.: Histogram showing the amount of flares per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins (a)/30 bins (b) of the phase, showing the number of flares per bin. The error bar shows the standard deviation for 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 4.2a to 4.3b), makes the trend of figure 4.1b 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 4.2a, 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 4.1b) are visible. Comparing to the dip visible in figure 4.1a, 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 4.2b. 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 4.3a. 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 previous figures mentioned dips.

Increasing the bin count to 30 (see figure 4.3b) 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.

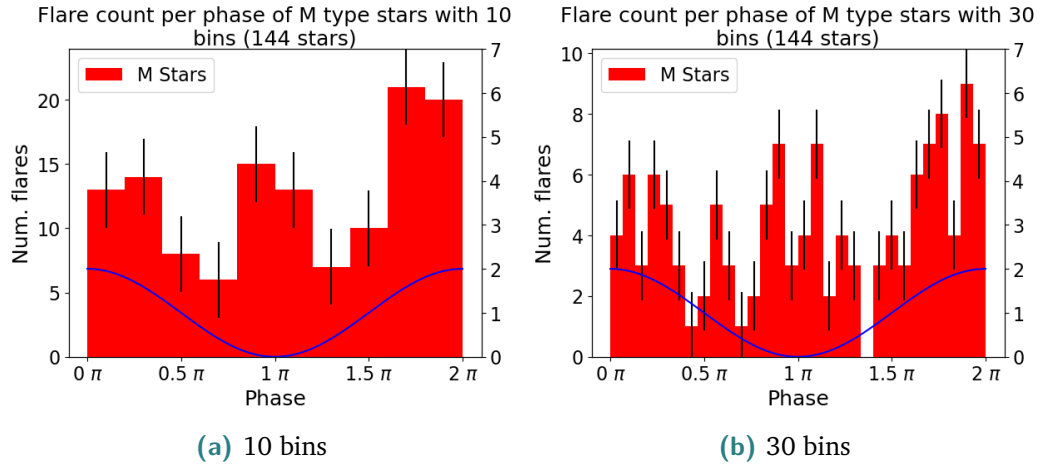


Fig. 4.2.: Histograms showing the amount of flares with a normalized peak of greater than 1.25 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a) /30 (b) bins of the phase, showing the number of flares per bin. The 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 .

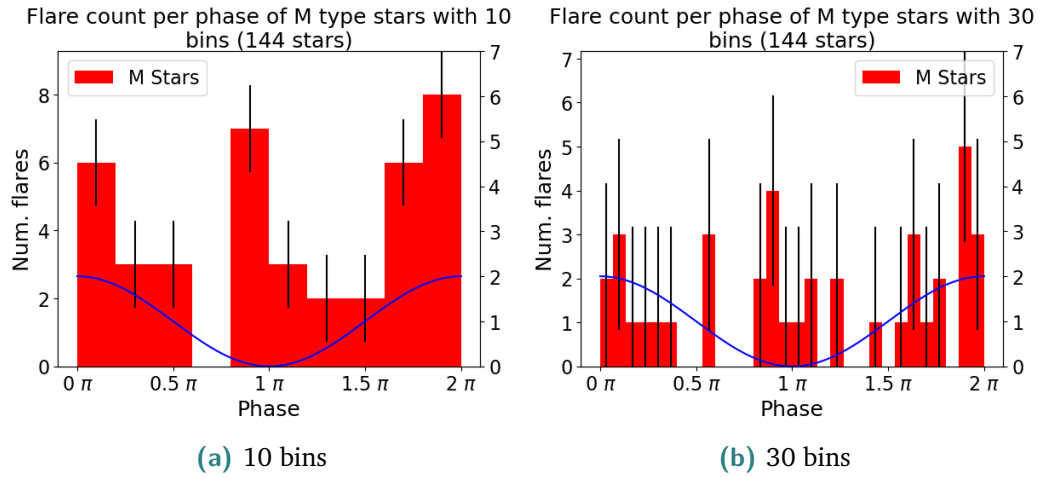


Fig. 4.3.: Histograms showing the amount of flares with a normalized peak of greater than 1.5 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The error 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 .

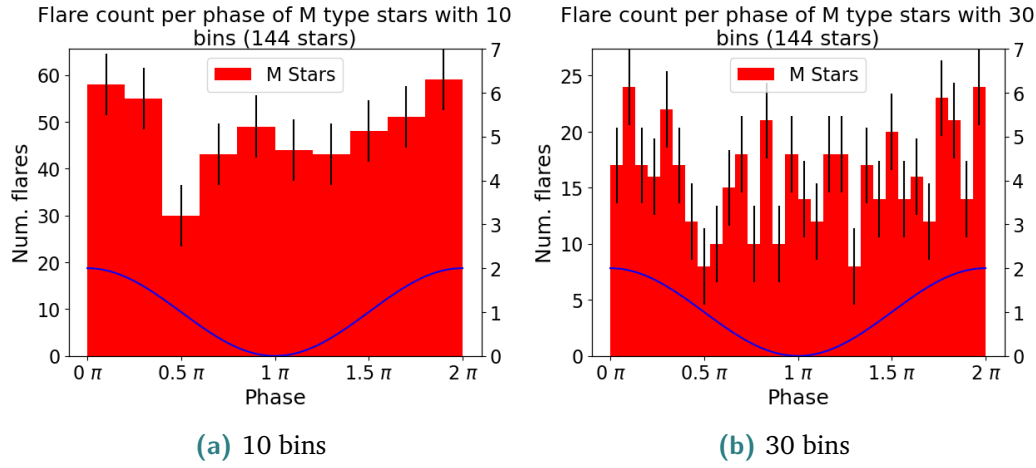


Fig. 4.4.: Histograms showing the amount of flares with a normalized peak of less than 1.01 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The error 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 .

Doing the opposite and only plotting the histograms for flares with normalized peaks of less than 1.01 can be seen in figure 4.4. Figure 4.4a shows a similar picture to the histogram with no limits on flare peaks (see figure 4.1a). The difference here though is that there are less flares in the area of the minima around phase 0.5π to 1.5π . Increasing the bins to 30 (figure 4.4b) shows overall a similar pattern, even though the differences between bins, especially in the center during the phase minima can be larger than twice the error.

Limiting the normalized flare peaks to <1.05 (figure 4.5) shows again similar pattern to the histograms with all data. In figure 4.5a the major difference is that there is a peak around normalized phase 1.1π , which would be during the folded lightcurve minima. The difference becomes less obvious when increasing the bin size 30 (figure 4.5b). While overall the same are visible, there appears a new dip around phase 0.25π which is right after the maximum. Also the shape of the peak consisting of multiple bins around phase 1.1π changed slightly compared to the one in figure 4.1b.

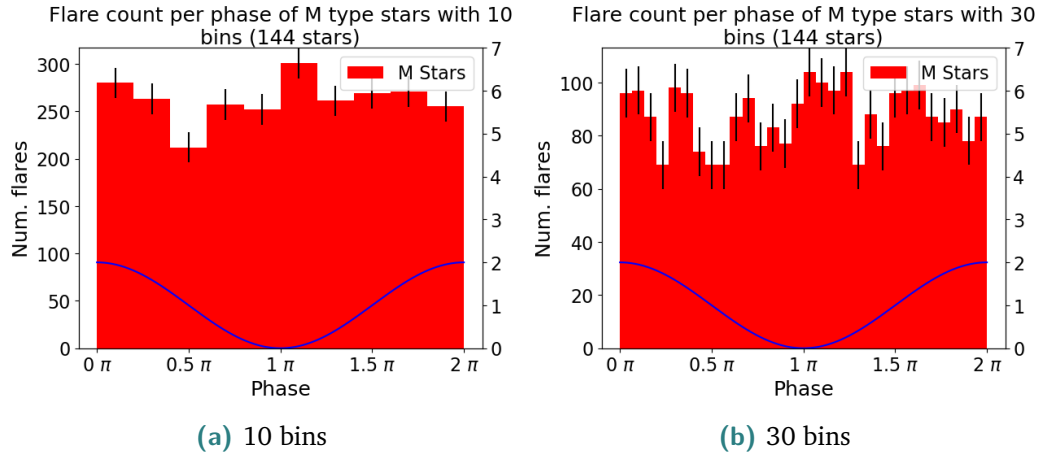


Fig. 4.5.: Histograms showing the amount of flares with a normalized peak of less than 1.05 per phase for all 144 M dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The error 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 4.6a 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 4.6b), the peak in the phase minimum at 1π is still visible. Additionally there appear more peaks at phase $> 1.3\pi$ ($1.3, 1.6, 1.9\pi$), 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 4.6a with 10 bins. The major dips at phase $0.7\pi, 1.3\pi, 1.6\pi$ 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.

The histograms with limited normalized flare peaks to > 1.05 is shown in figure 4.7. In 4.7a the histogram with 10 bins is shown, while figure 4.7b shows the histogram with 30 bins. There are multiple clear peaks visible in figure 4.7a. The

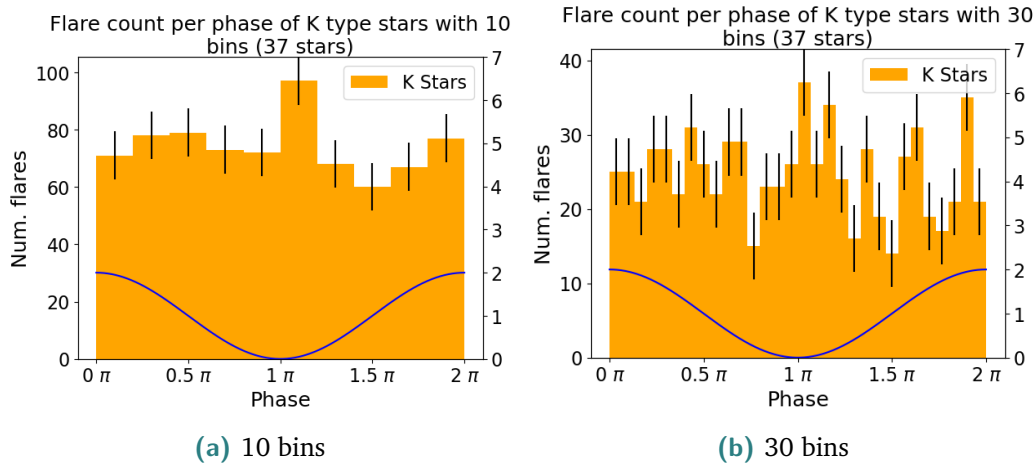


Fig. 4.6.: Histogram showing the amount of flares per phase for all 37 K dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins (a)/30 bins (b) of the phase, showing the number of flares per bin. The error bar shows the standard deviation for 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 .

two highest being at phases 0.7π as well as 1.1π , with the latter being wider having a decline till the phase maximum is reached. These two peaks are separated by a bin at phase 0.9π which is significantly lower (roughly twice the errorbar size). Additionally there appears a peak just slightly smaller than the other two in the first bin (at phase maximum).

A similar picture forms when increasing the bin count to 30 (figure 4.7b). The main differences to 10 bins is though that the heights of the aforementioned peaks is now the same, and that the errorbars started to overlap with the surrounding bins. Additionally a new peak in the last bin, during the phase maximum, appeared having the same height as the other three.

Similarly to what has been done to the histograms in section 4.1, figures 4.8 and 4.8 limit the data used to plot the histograms to flares with a normalized peak of less than 1.01 and 1.05 respectively. In figure 4.8a, which limited the flare peaks to a maximum of 1.01, there appears a significantly large peak at around phase 1.2π which is at the phase minimum. Another, slightly smaller peak appears at the phase maximum at 1.9π . Both of these peaks are, including error, higher than the average flare count. Checking for more specific phases for the peaks, by increasing the bin count to 30, shows an overall decrease in flares at the phase maximum at around phase $0/2\pi$, but shows significant peaks at phases 1.6π and 1.9π . These two bins are now larger than the one(s) at around phase 1π to 1.2π .

Increasing the allowed flare peaks to 1.05 in figure 4.9 shows a similar pattern to what happened in figure 4.5 with the data for M dwarfs. The resulting histogram look very similar to the ones using all available flare data for K dwarfs (figure 4.6).

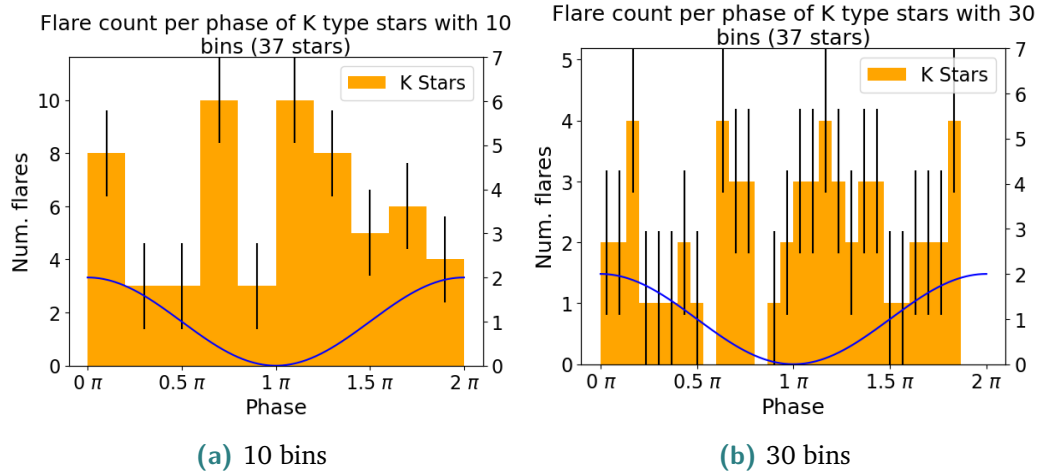


Fig. 4.7.: Histograms showing the amount of flares with a normalized peak of greater than 1.05 per phase for all 37 K dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The error 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 .

The differences of figure 4.9a, which shows the histogram with 10 bins with flare peaks limited to <1.05 , and 4.6a, which shows the histogram with 10 bins for all detected flares of K dwarfs, is that the two bins at around phase 1.3π to 1.5π are now more prominent, even though still not outside of the error of their surrounding bins. Similarly the last bin at around phase 1.9π is more prominent.

Increasing the bins to 30 (figure 4.9b) shows a very similar figure to as figure 4.6b with 30 bins without any limits to flare peaks. There only very slight differences in the relative bin height.

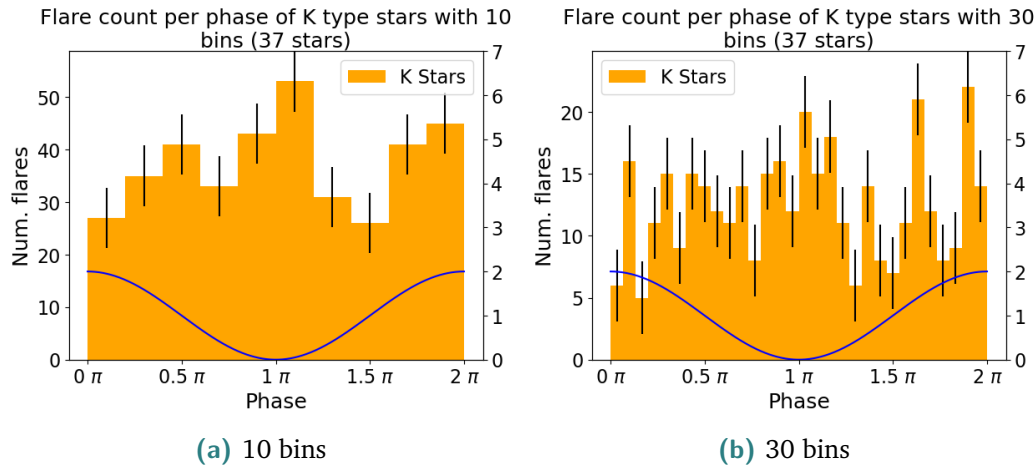


Fig. 4.8.: Histograms showing the amount of flares with a normalized peak of less than 1.01 per phase for all 37 K dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The error 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 .

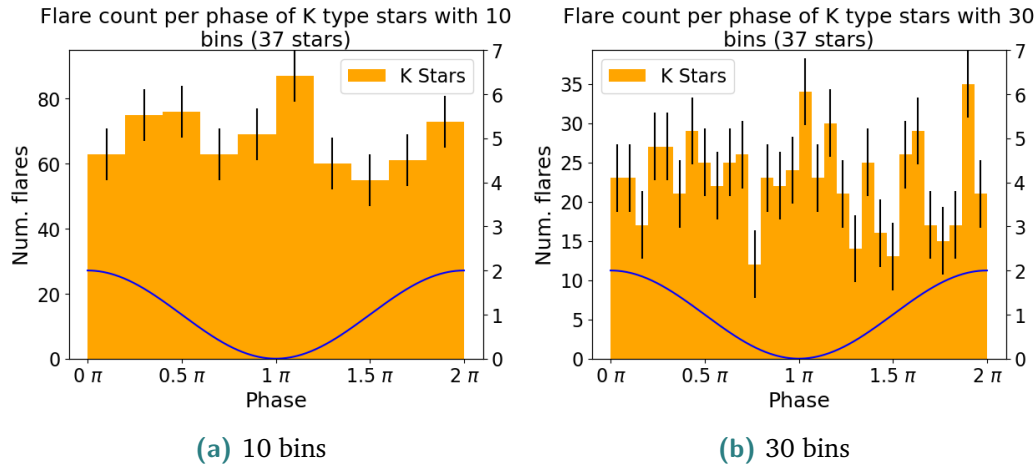


Fig. 4.9.: Histograms showing the amount of flares with a normalized peak of less than 1.05 per phase for all 37 K dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The error 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 .

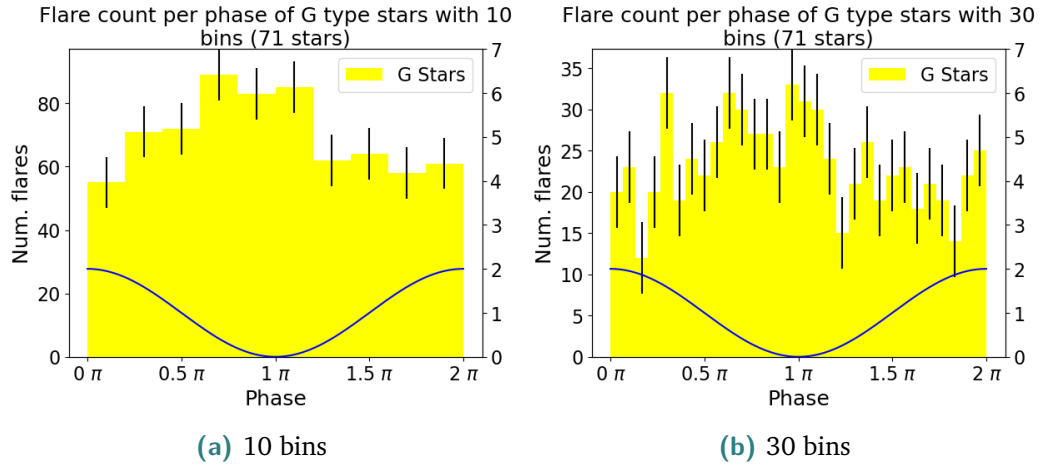


Fig. 4.10.: Histogram showing the amount of flares per phase for all 71 G dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins (a)/30 bins (b) of the phase, showing the number of flares per bin. The error bar shows the standard deviation for 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 4.10a 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 4.10b 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 4.10a becomes more noisy, even though it's still well within error.

Limiting the flare peaks to <1.05 (figure 4.11) does not change the resulting histograms much. There are only miniscule differences, mainly the bin at phase 1.1π is now slightly smaller relative to the two prior bins in figure 4.11a compared to figure 4.10a with all flares.

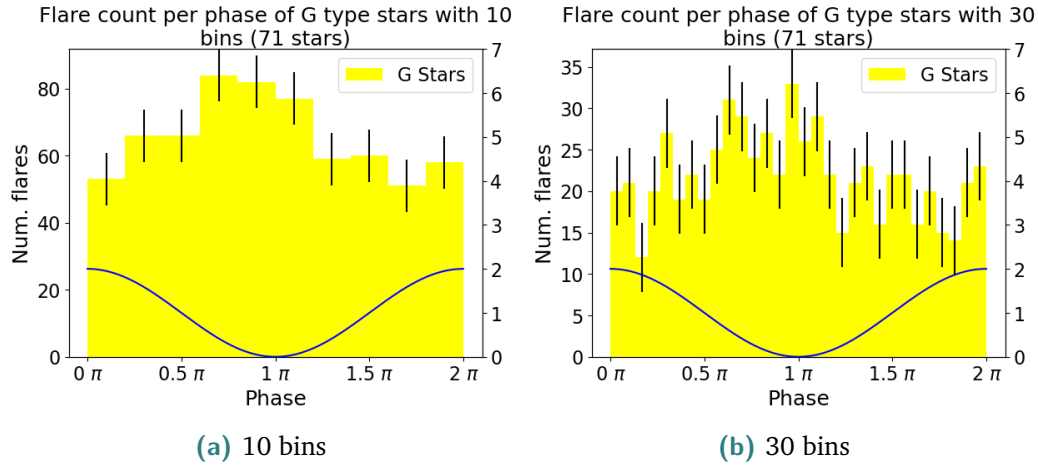


Fig. 4.11.: Histograms showing the amount of flares with a normalized peak of less than 1.05 per phase for all 37 K dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The error 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 .

Looking only at flares >1.05 on the other side significantly changes how the histograms look like. Figure 4.12a shows the histogram with 10 bins, while figure 4.12b shows the one with 30 bins. The histogram with 10 bins shows 3 significant peaks. The first at around phase 0.5π with a width of 3 bins, the second at around 1.1π and the last at around 1.7π . All of these peaks are well above their surrounding bins including errors.

Increasing the bins to 30, which is seen in figure 4.12b, does not give such a clear picture. Due to the overall lower total number of flares due to the limit, and the increased bin count, all errorbars are overlapping. Even though there are still singular bins at 0.4π , 1.1π and 1.7π which are higher than their surroundings, but not outside the error range anymore.

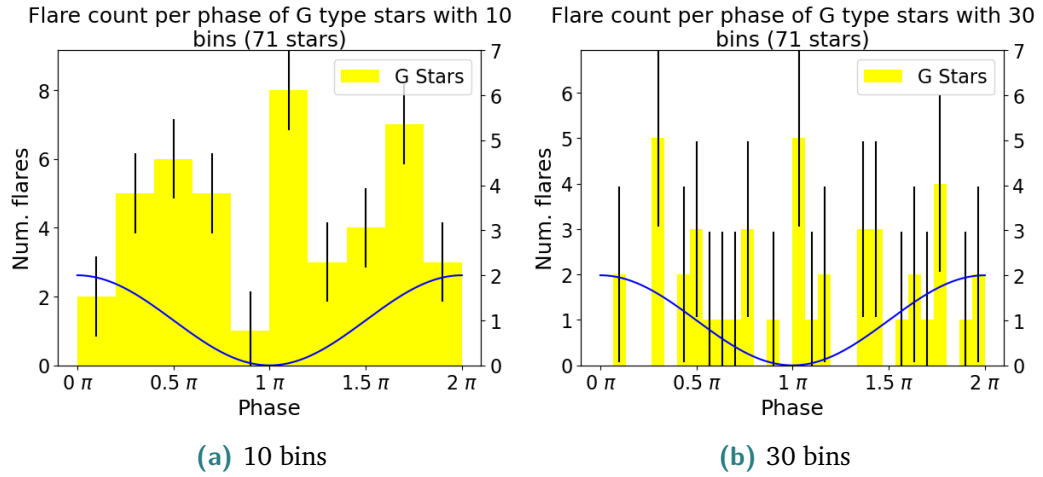


Fig. 4.12.: Histograms showing the amount of flares with a normalized peak of greater than 1.05 per phase for all 71 G dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 (a)/30 (b) bins of the phase, showing the number of flares per bin. The 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 4.13a and 4.13b 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.

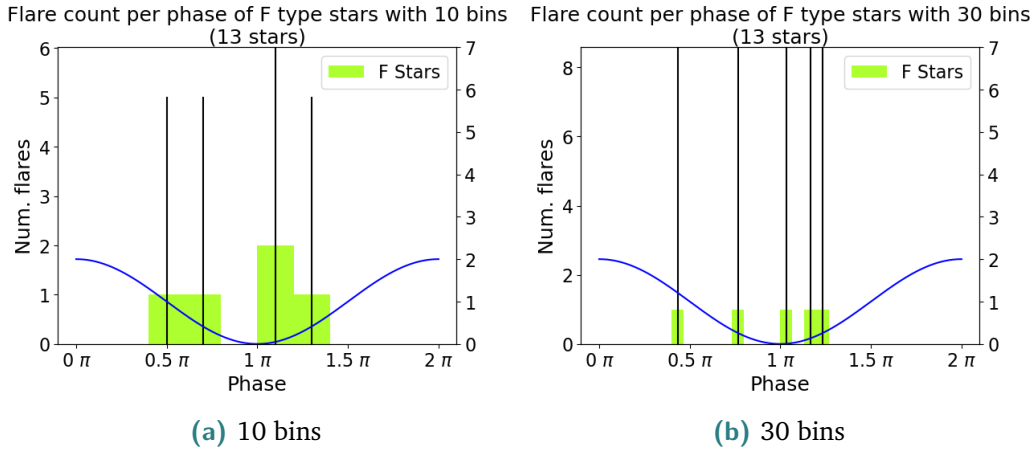


Fig. 4.13.: Histogram showing the amount of flares per phase for all 13 F dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins (a)/30 bins (b) of the phase, showing the number of flares per bin. The error bar shows the standard deviation for 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 4.14a and 4.14b 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 4.1a in section 4.1) propagates and causes the dip to be also visible in figure 4.14a. 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 4.14b, 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 4.6b) and G (figure 4.10b) 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 .

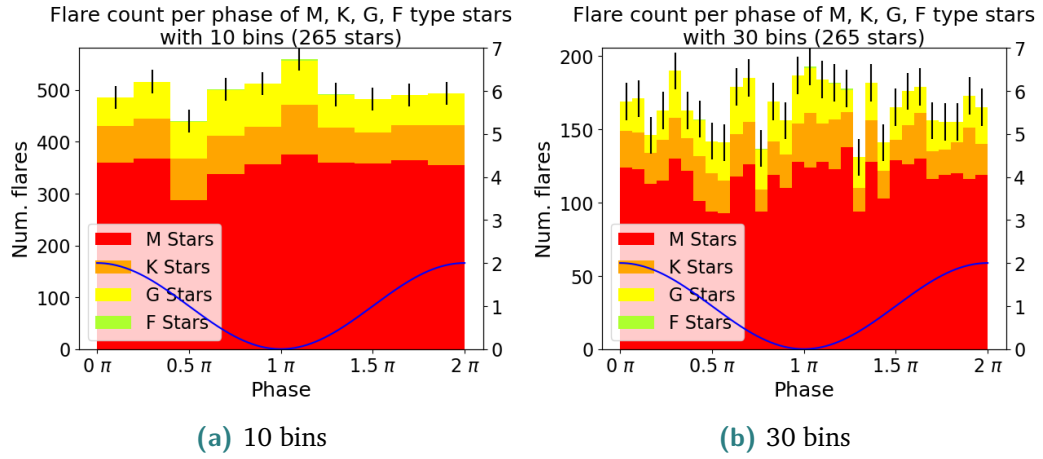


Fig. 4.14.: Histograms showing the amount of flares per phase for all 265 dwarfs used in this study. The x-axis represents the normalized phase of the folded lightcurves. There are 10 bins (a)/30 bins (b) of the phase, showing the number of flares per bin. The colors show the individual amount for each 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 BD-08 995

BD-08 995, also known by TIC 43472154, is a G type star with a surface temperature of 5231.2 K, which is ~ 87 pc away. It is a very active solar like star, producing over 200 superflares per year (Tu et al. (2020)). It has a rotational period of 2.8 days (Tu et al. (2020)). There are two TESS lightcurves available, sectors 5 and 32.

Looking at figure 4.15a, which shows the flare distribution across the normalized phase of the folded lightcurves with 10 bins, it shows a clear peak of flares appearance in the lightcurve minima at phase 1π . The errorbars of this wide peak only overlap with the first bin of the plot at phase 0π . This bin belong to the phase maxima which also shows slight increase in flare activity at phase $0/2\pi$ compared to the transition regions at around phase 0.5π (maxima to minima) and 1.5π (minima to maxima). Considering errors for this, the errorbars of the bins at the phase maxima overlap with those of the transition regions.

Figure 4.15b shows the same data just with 30 bins instead of 10. Ignoring the

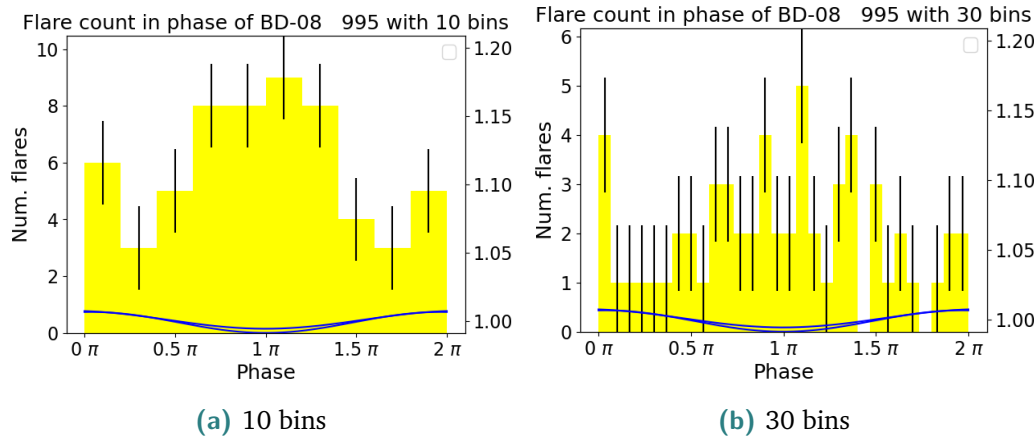


Fig. 4.15.: Histograms of BD-08 995 across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

errorbars, it shows a similar picture as the previous figure. But due to the low number of total detected flares, and a the relatively large bin count, the errorbars become large compared to the individual bins. Due to this, the errorbars of most bins overlap with each other, with the exceptions of the the first bin at phase 0π and the bin at phase $\sim 1.1\pi$, whichs errorbars only overlap with other higher bins like the ones at phase $\sim 0.9\pi$ and $\sim 1.4\pi$.

The distribution of normalized flare peaks for BD-08 995 in figure 4.16 shows that the highest flare peak appeared at around phase 0.1π with a peak of ~ 1.11 . Other high flare peaks were detected at phases $\sim 1\pi$ and $\sim 1.9\pi$. Furthermore the flares around phase 1π seem to have higher average peak.

Looking at the folded TESS lightcurves of sector 5 (4.17a) and 32 (4.17b) one can see the earlier presented distribution of flares and their peaks. In TESS sector 5 there appear comparatively many flares at around phase -0.2 (not normalized). The highest detected flare peak which was mentioned prior was detected in the TESS sector 32 lightcurve at phase -1.2 .

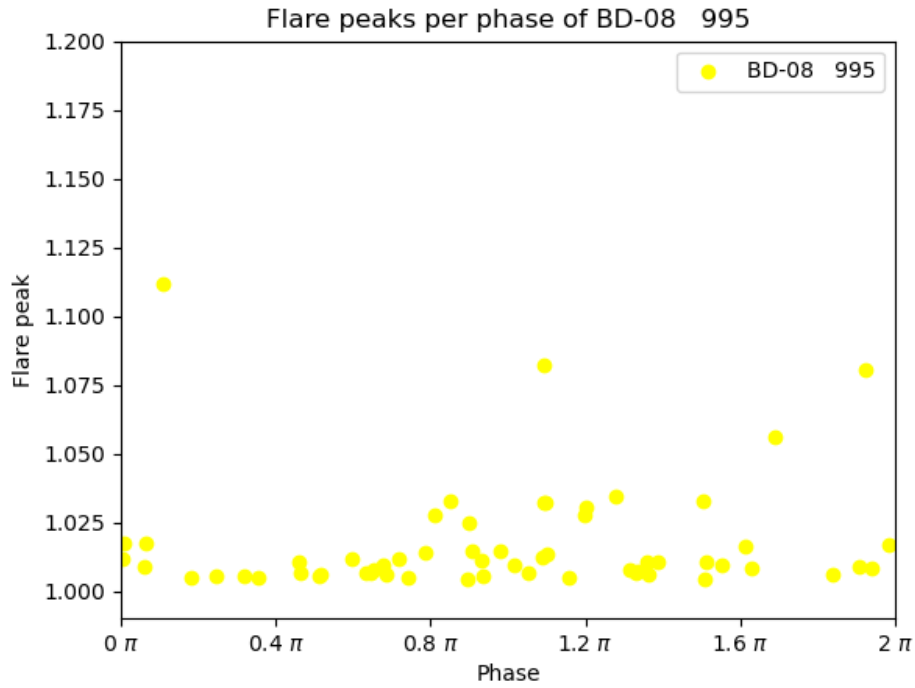


Fig. 4.16.: Distribution of flare peaks in relation to the normalized phase at which they occurred for BD-08 995. Y-Axis shows the flare peak and is limited to the value of the highest peak detected. The x-axis shows the normalized phase.

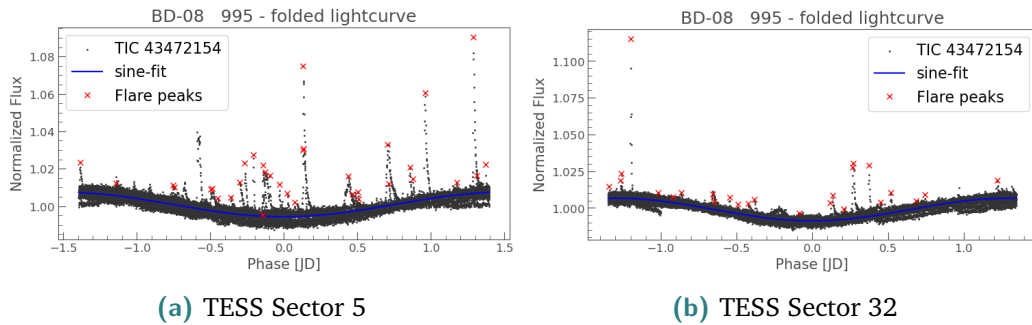


Fig. 4.17.: Folded lightcurves for BD-08 995. The blue lines shows the sine fits calculated. The red crosses indicate the detected flare peaks.

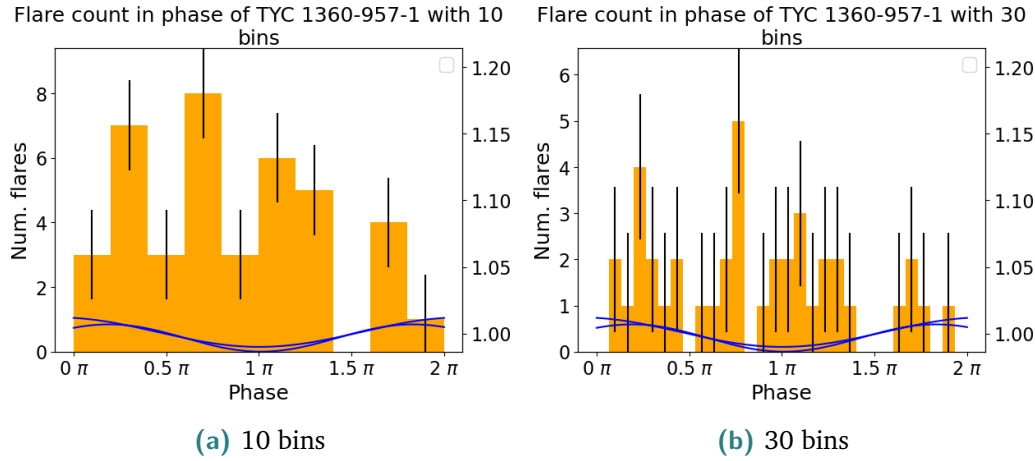


Fig. 4.18.: Histograms of TYC 1360-957-1 across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

4.6.2 TYC 1360-957-1

Not much is published about TYC 1360-957-1. It has been categorized as spectral type K on SIMBAD (Wenger et al. (2000)). It has the TESS Input Catalogue number 247117382, and has been observed by TESS in sectors 44, 45 and 46.

Looking at the flare distribution histogram with 10 bins for this star in figure 4.18a one can see that the highest peaks in order are at phase $\sim 0.7\pi$, $\sim 0.4\pi$ and $\sim 1.2\pi$. The last one being two bins wide. The first two are, including error, above their surrounding bins, while for the third peak, the second peaks errorbar overlaps with those of the smaller bins. Looking at the histogram with 30 bins of the same dataset (figure 4.18b), the first 2 peaks mentioned for the histogram with 10 bins are still visible. But compared to the previous figure, the low number of flares result in a rather large error. This causes the errorbars of the two mentioned bin peaks to overlap with the surrounding bins which could be estimated to be the average.

Figure 4.19 presents the overall distribution on the normalized phase detected for TYC 1360-957-1 in this study. The three highest flare peaks detected were at a normalized phase of $\sim 0.8\pi$, which is very close to the phase minimum at 1π . Three more higher flare peaks stand out at phase 1.2π . While they are not as high as the previous three, they have a higher peak than the rest of the detected flares.

The used folded lightcurves used can be seen in figure 4.20. This figure is split into the three different TESS sectors. In a sector 44 is visible. The lowest point of the folded lightcurve is slightly shifted from the center, which represents the lowest

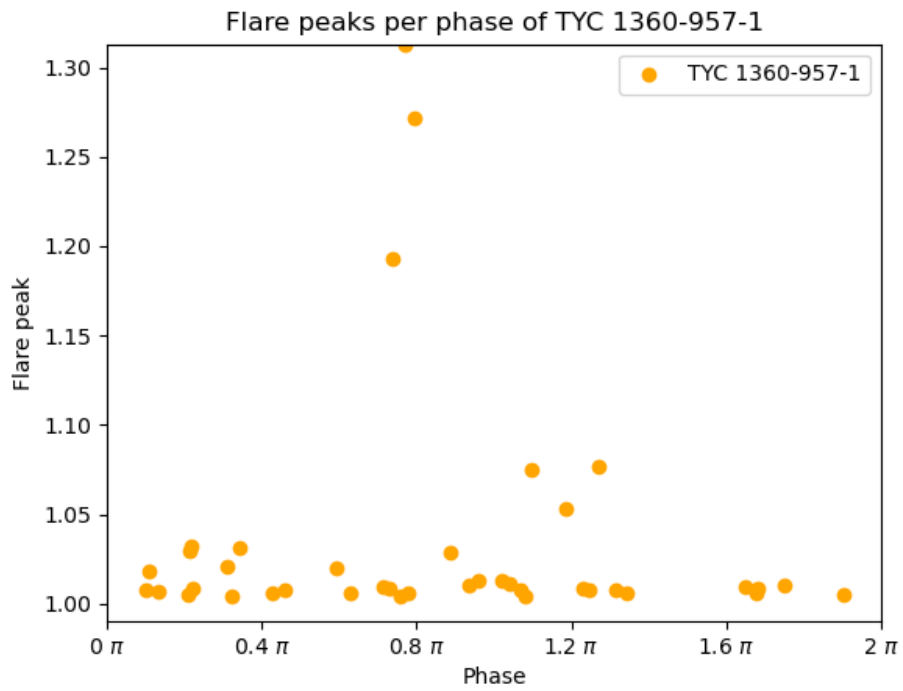


Fig. 4.19.: Distribution of flare peaks in relation to the normalized phase at which they occurred for TYC 1360-957-1. Y-Axis shows the flare peak and is limited to the value of the highest peak detected. The x-axis shows the normalized phase.

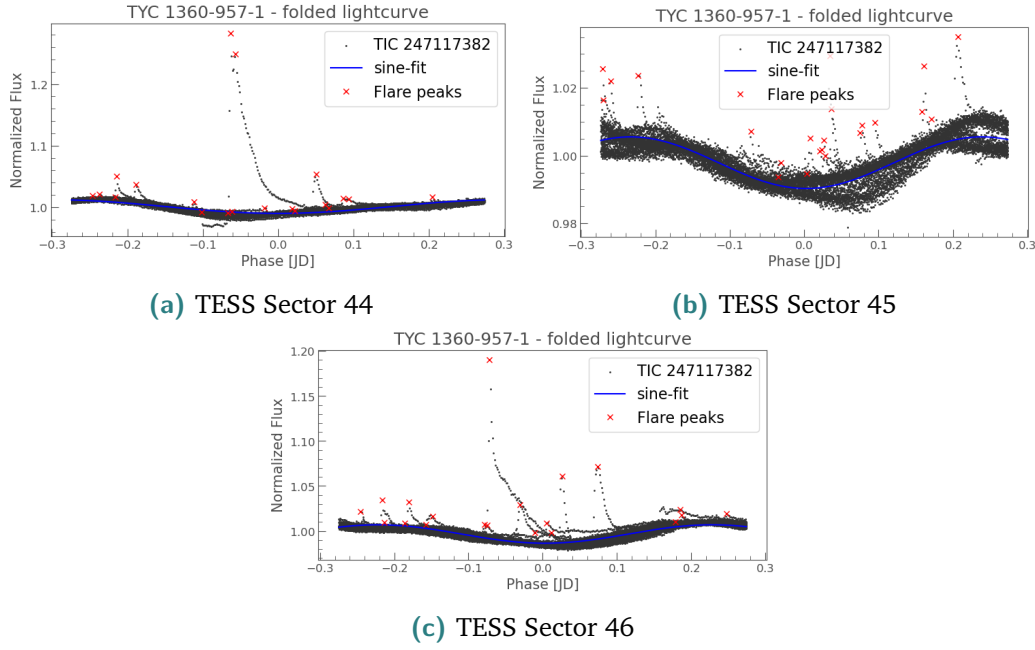


Fig. 4.20.: Folded lightcurves for TYC 1360-957-1. The blue lines shows the sine fits calculated. The red crosses indicate the detected flare peaks.

point of the sine fit. One can also see that two large flares happened at this point. No such large flares can be seen in **b**, unlike in **c** which shows a large flare again.

4.6.3 TYC 4595-107-1

TYC 4595-107-1, also known as TIC 394030788, is a G type star with an effective temperature of 5231 K, a radius of $0.9 R_{\odot}$ (Tu et al. (2021), Crowley et al. (2022)), mass of $0.89 M_{\odot}$ (Crowley et al. (2022)) and a rotational period of 3.3 days (Tu et al. (2021), Crowley et al. (2022)) and was observed in 20 TESS sectors. The folded lightcurves for TYC 4595-107-1 can be found in appendix B.1.

The first histogram, figure 4.21a, with 10 bins shows the accumulated data for all 20 observed lightcurves. Due to the high number of available lightcurves, and TYC 4595-107-1 being a very active star (Tu et al. (2021), Crowley et al. (2022)), the total flare count is very high. There seems to be a base level of flares per bin of around 30 over the phase, with a large and two bin wide peak at around phase 0.6π to 0.8π . This increase in flares is high enough to be outside of the error of the base amount of flares. Another peak, even though less certain as its errorbar overlaps with the surrounding bins, appears at the bin at phase 1.9π . A similar increase in flares can be seen at the bin at 0.2π .

The histogram with 30 bins (figure 4.21b) shows a similar result. It shows a large increase in flares around phase 0.6π to 1π , as well as at 1.9π to 0.1π and 0.4π . Only the

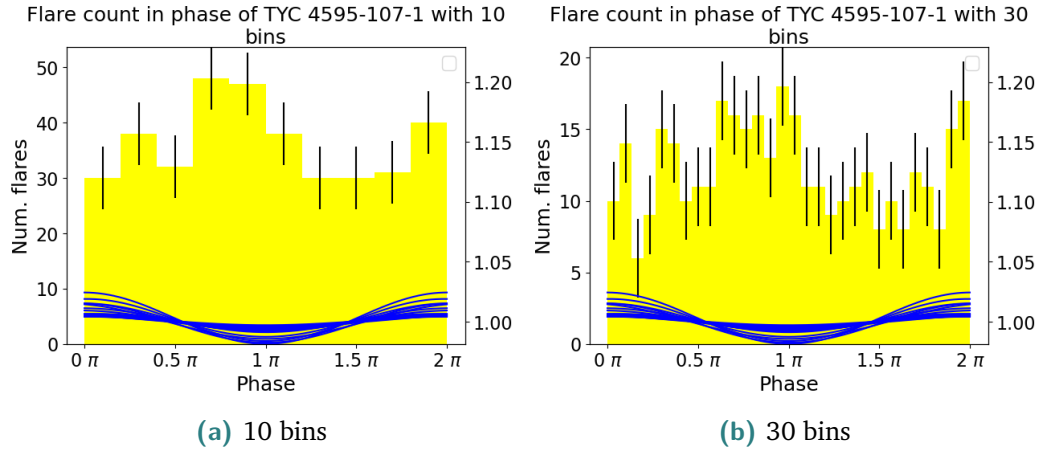


Fig. 4.21.: Histograms of TYC 4595-107-1 across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

first mentioned peak managed to be large enough though, to not have overlapping errors with the surrounding lower count bins.

The flare peak at normalized phase distribution can be seen in figure 4.22. The strongest flare was detected at normalized phase $\sim 0.8\pi$. Two slightly higher flare peaks have been detected at phases 0.5π and 2π respectively, but otherwise there does not seem to be any pattern.

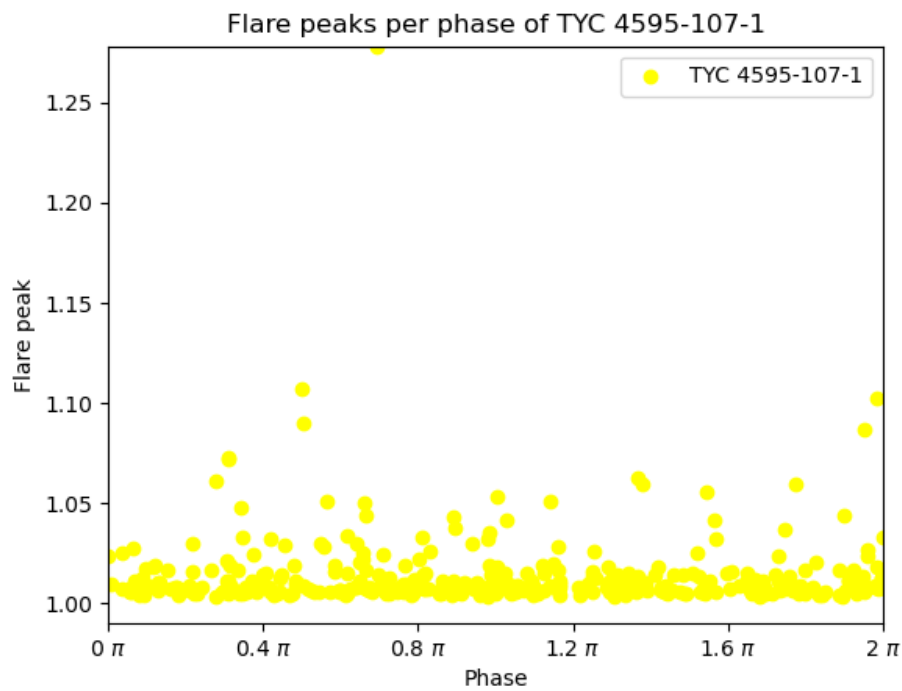


Fig. 4.22.: Distribution of flare peaks in relation to the normalized phase at which they occurred for TYC 1360-957-1. Y-Axis shows the flare peak and is limited to the value of the highest peak detected. The x-axis shows the normalized phase.

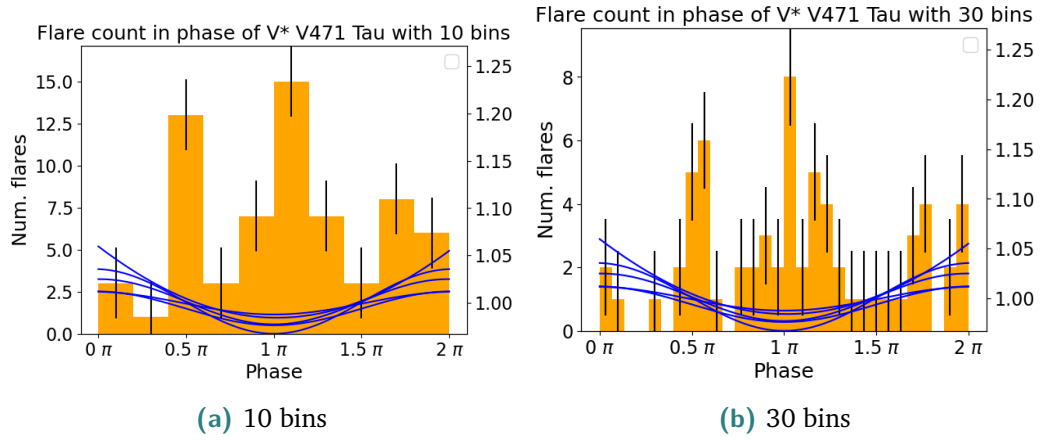


Fig. 4.23.: Histograms of V471 Tau across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

4.6.4 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 (Kővári et al. (2021)). Figures 4.23a and 4.23b 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 4.24a, 4.24b and 4.24c 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 4.23b) 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 4.24a, 4.24b and 4.24c), the transit of the white dwarf (sudden dip in the folded lightcurve) is clearly visible, and always happens around phase 0.

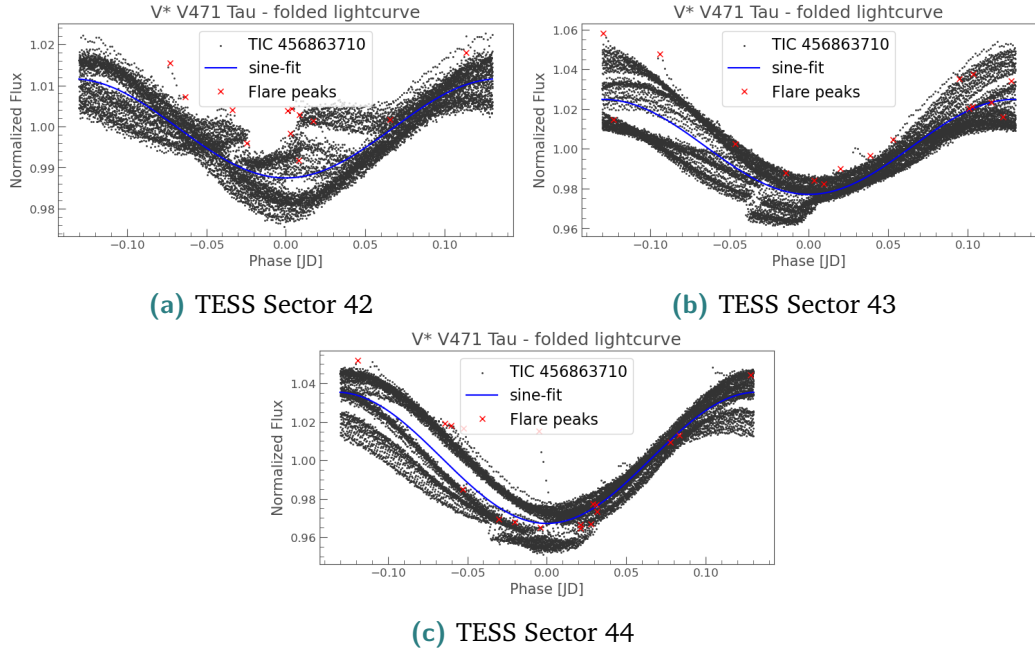


Fig. 4.24.: Folded lightcurves for V* V471 Tau. The blue lines shows the sine fits calculated. The red crosses indicate the detected flare peaks.

Figure 4.25 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 .

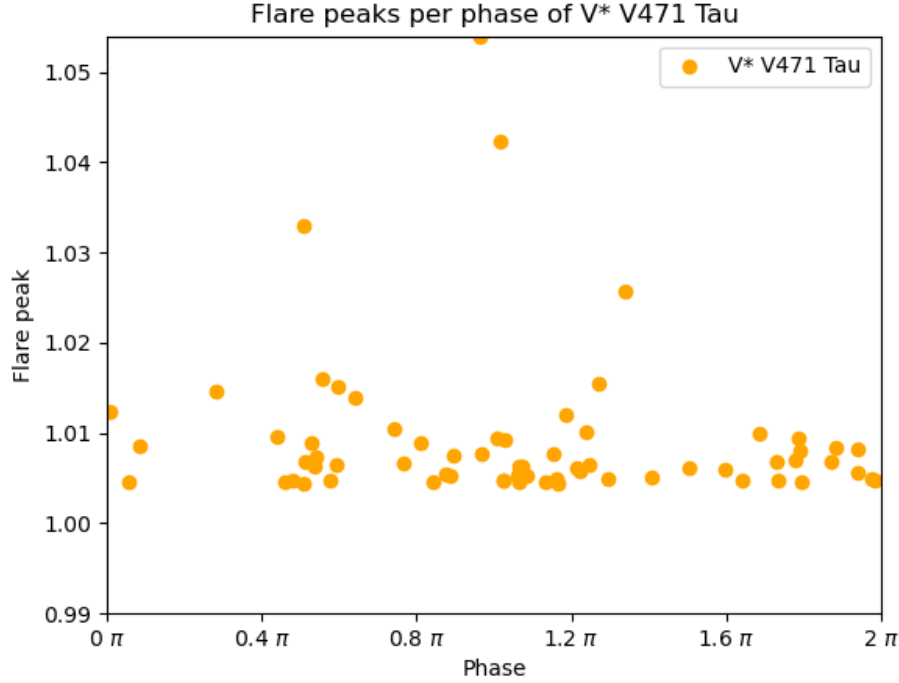


Fig. 4.25.: Distribution of flare peaks in relation to the normalized phase at which they occurred. Y-Axis shows the flare peak and is limited to the value of the highest peak detected. The x-axis shows the normalized phase.

4.6.5 V* HK Aqr

HK Aqr is a M dwarf with a mass of $0.57 M_{\odot}$, a radius of $0.53 R_{\odot}$ and is around 22.3 pc away from our solar system. Its effective temperature is around 3800 K (Gaidos et al. (2014)). It was observed in four TESS sectors. HK Aqr is mentioned here, as it is a star, for which the optimize fold algorithm partially broke. This happened for its lightcurves for the sectors 29 and 42. The algorithm found for both periodograms a second signal for a possible period. This resulted in the folded lightcurves seen in figures 4.27b and 4.28a. Figures 4.26a and 4.26b were created with this dataset.

In figure 4.26a one can see an increase in flares at around phase 1.3π . This peak is high enough to be outside the error range of the lower flare count bins between phase 0 to 1π . Figure 4.26b paints a similar picture. Additionally it shows a peak at phase 0π though, which is during the phase maximum, as well as one at around phase 1.6π which is in the transition from minima to maxima.

Figures 4.29a and 4.29b show the histograms for the data of the two folded TESS lightcurves of sectors 29 and 42 which were flagged as period folded with 10 and 30 bins respectively. The folded lightcurves can be found in figure 4.30. In figure 4.29a the overall flare distribution seems to be relatively high from phase 0.2π to 1.4π , with a peak at phase 1.2π . The amount of detected flares during the maximum of the lightcurves at phase 1.8 to 0.2π is low compared to that. Even including the

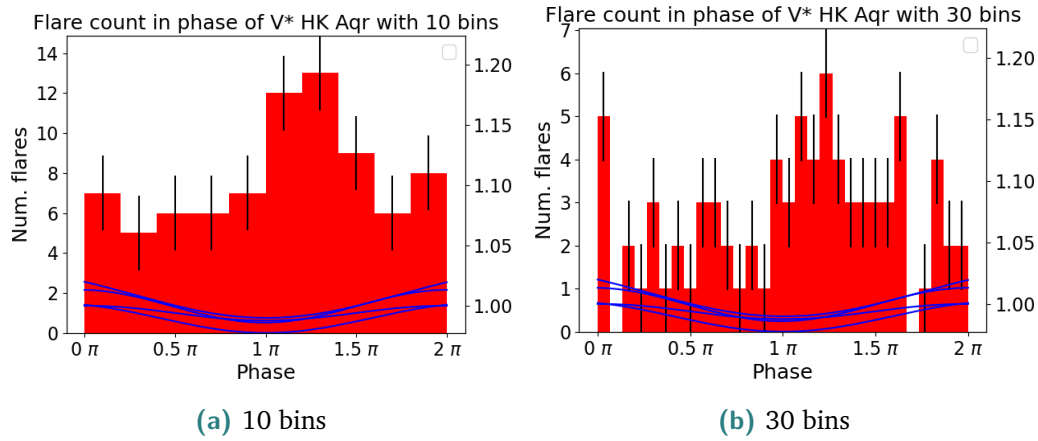


Fig. 4.26.: Histograms of V* HK Aqr across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

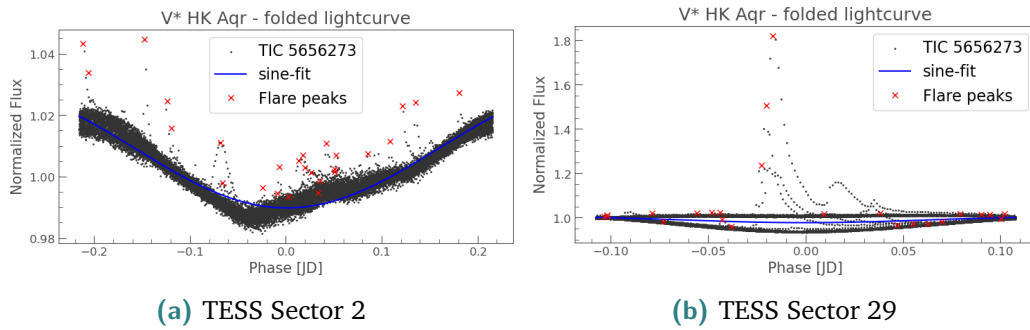


Fig. 4.27.: Folded lightcurves for V* HK Aqr. The blue lines shows the sine fits calculated. The red crosses indicate the detected flare peaks.

errorbars it cannot reach the previous bins. An additional dip of the same flare count can be seen at phase 1.5π . The flare count in figure 4.29b is very low. Due to this all errorbars overlap. Nonetheless there are two bins which stand out at phases $\sim 0.4\pi$ and $\sim 1.25\pi$ which would be in the transition from maxima to minima, and shortly after the minima respectively.

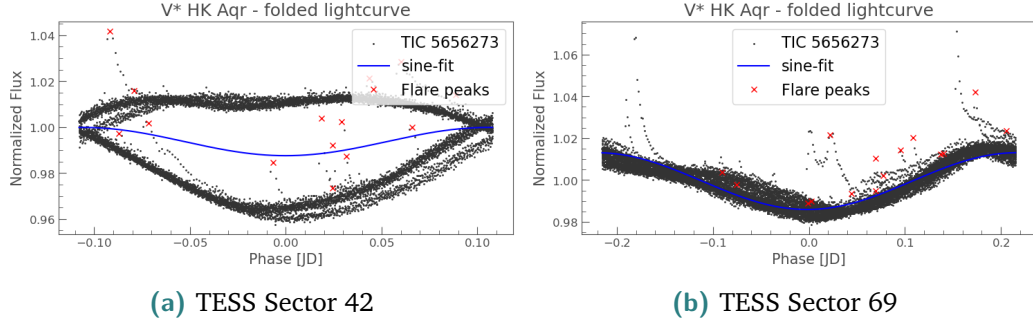


Fig. 4.28.: Folded lightcurves for V* HK Aqr. The blue lines shows the sine fits calculated. The red crosses indicate the detected flare peaks.

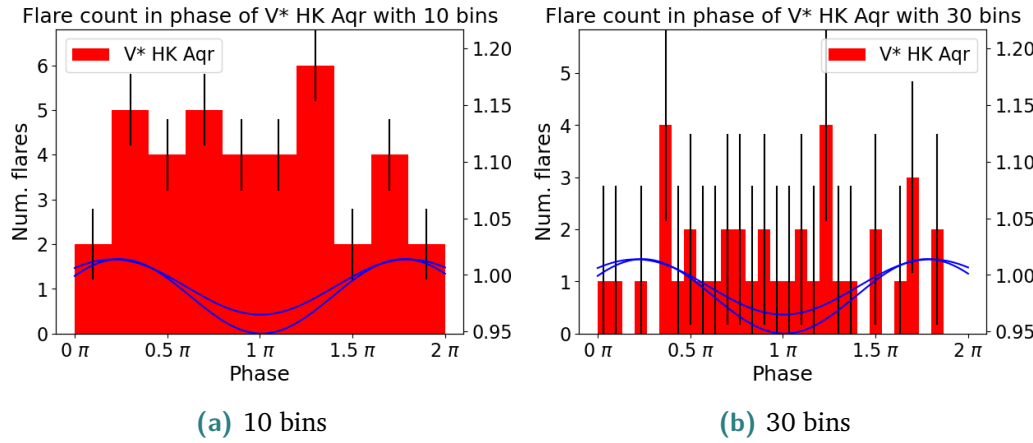


Fig. 4.29.: Histograms of V* HK Aqr across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

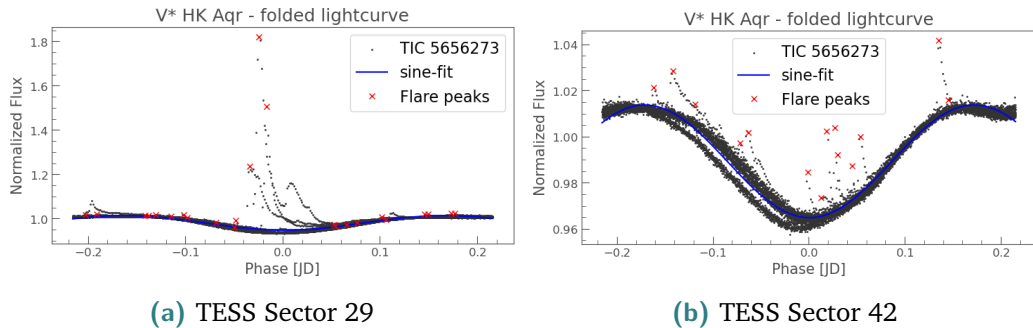


Fig. 4.30.: Folded lightcurves for V* HK Aqr. The blue lines shows the sine fits calculated. The red crosses indicate the detected flare peaks.

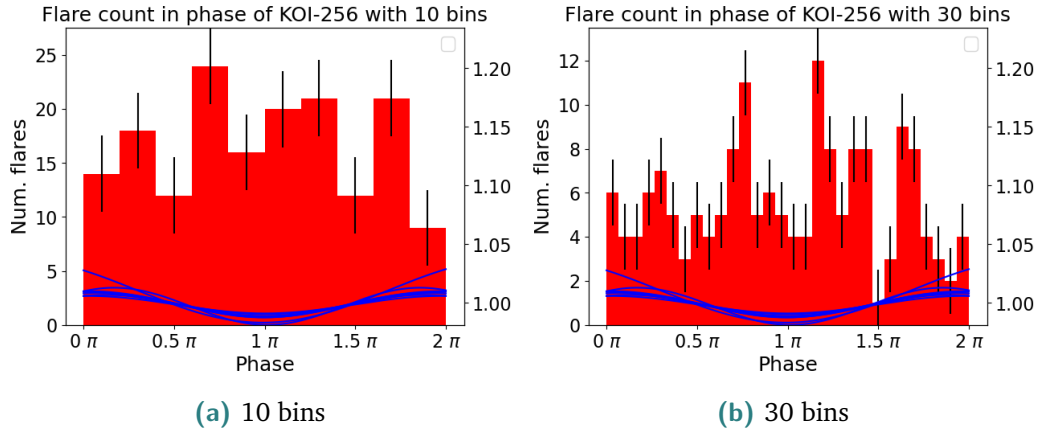


Fig. 4.31.: Histograms of KOI-256 across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

4.6.6 KOI-256

KOI-256 is, similarly to V471 Tau, a binary system consisting of a M dwarf and a white dwarf (Muirhead et al. (2013), Morgan (2017)). It has a mass of $0.51 M_{\odot}$, a radius of $0.540 R_{\odot}$ and an effective temperature of 3450 K (Muirhead et al. (2013)). Similarly to HK Aqr, a second periodicity was detected, which was the used to fold for spot modulation. This happened for Kepler target table ids 37, 38, 53 and TESS sector 80.

Figure 4.31a shows the histogram with 10 bins for KOI-256 with all detected spot modulations, including the mentioned ones that were wrongfully detected. This figure shows a increase in flare count around phase 1π , which peaks at phases 0.7π and around 1.4π . Additionally there appears a peak at phase 1.7π . Increasing the bins to 30 (figure 4.31b) shows clearer peaks at phase 0.7π as well as 1.2π . Including errorbars, the mentioned peaks of both figures are above their surrounding bins.

Figures 4.32a and 4.32b show the histograms based on the, by the optimized fold algorithm determined, period folded lightcurves. Therefor only the period folded lightcurves from Kepler target table id 37, 38, 53 and TESS sector 80 were used. In figure 4.32a, which shows a histogram with 10 bins for the flare distribution across the normalized phase, there is a clear increase of flares seen around the minima at phase 1π . The distribution nearly reminds one of a normal distribution, with the exception that the last two bins around phase 1.8π to 2π do not fall off as much as the first bin at phase 0π does compared to the bins in the center.

Looking at figure 4.32b which shows the same data, just with 30 bins, the peak at the phase minimum at 1π is still present. Additionally there are three more peaks

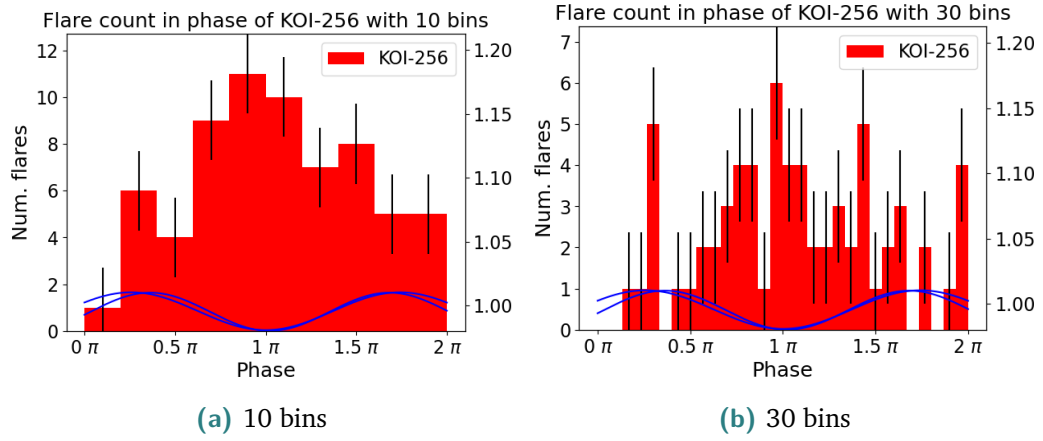


Fig. 4.32.: Histograms of KOI-256 across the phase showing the number of flares in each bin. The error bar shows the standard deviation for the histogram. The blue lines show the various fits for the folded lightcurves used to generate the data, with the phase minimum at 1π and phase maximum at $0\pi/2\pi$.

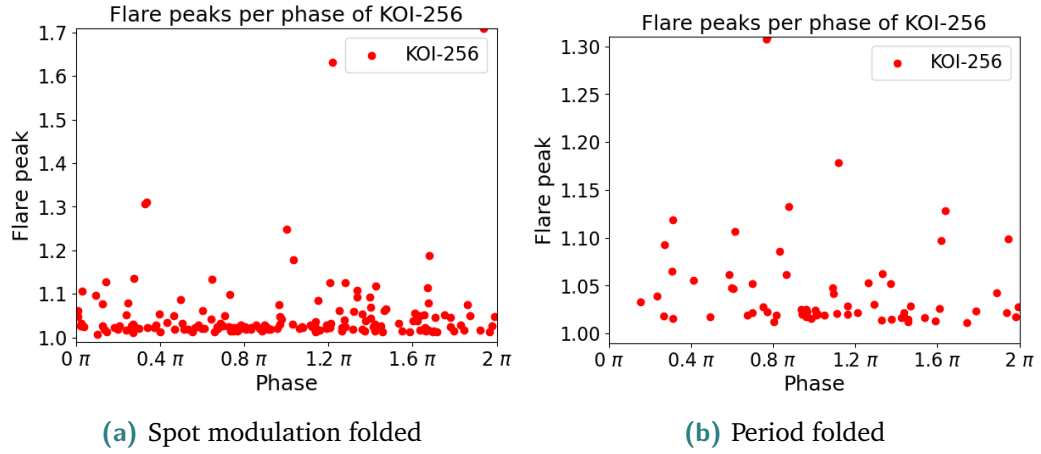


Fig. 4.33.: Distribution of flare peaks in relation to the normalized phase at which they occurred. Y-Axis shows the flare peak and is limited to the value of the highest peak detected. The x-axis shows the normalized phase.

visible at around phases 0.3π , 1.4π and 2π . These three peaks are only 1 bin wide and stand out far from their surrounding by around 1.5 times the errorbar. The peak in the center on the otherhand has gradual increases/decreases before and after, with the exception of the dip in the bin right before at around phase 0.9π .

Comparing the results of the flare peak distributions across the normalized phases of the two datasets in figure 4.33 shows that the highest normalized flare peaks of up to 1.7 were detected in the lightcurves with proper period detection. Comparing flare peaks which exist in both data sample, one can see that the highest peak of b at around phase 0.8π and a normalized peak of ~ 1.3 was moved to around phase 0.4π in figure a due to the additional found periodicity.

Discussion

M dwarfs, all data, no significant dependency of flare appearance on phase using 10 bins. 30 bins -> either 2 dips during the transition minima <-> maxima or increase of flare occurrence during minima and maxima. Looking at stronger flares only (min 1.25/1.5 flare peak) peaks during minima, stronger peak during phase maxima, in both 10 and 30 bin histograms. Limiting to max 1.01, makes dip (compared to all data) clearer. Generally more flares during maxima than minima. Limit to max 1.05, nearly identical histograms to all data. (different result to Roettenbacher and Vida (2018))

K dwarfs, all data, significant peak at phase minimum, peak dominated by V471 Tau (discussed later). Slightly more flares from maximum to minimum than minimum to maximum in 10 bins. 30 bins larger dips but also larger peaks in second half of phase compared to first half. limiting to min 1.05 -> three peaks, dip after maximum and on at phase 1π . gradual decrease after minimum. V471 Taus peaks at right before and right after phase minimum. limiting to <1.01 and 1.05, makes histogram look more and more like with all data, similarly to Roettenbacher and Vida (2018) peak in center (compared to their M/K plot), but additionally also peak at phase maximum. max 1.05 already most flares, very similar to with all data.

G dwarfs, significant results, increase of flare appearance during phase minimum. Most flares are <1.05 (flares on solar like stars that increase brightness by 0.1% to 1% already superflares, Maehara et al. (2012)) -> most/all detected flares superflares. Overall dependency on phase/spot appearance. Limiting to flares >1.05 -> flares during minima and transitions between minima <-> maxima, increasing bins -> more data would be required.

For F dwarfs, overall too little data, but the not significant amount detected all during phase minimum, could be similar to G dwarfs?

All data combined, peak at phase minimum dominated by G/K dwarfs, dip in transition maxima -> minima dominated by dip from M dwarf results.

Individual star results (subset taken): BD-08 995 (G type): shows a strong flare/spot dependence for amount, flare peaks not dependent on phase

TYC 1360-957-1 (K type): no clear dependence on spots for flare count (1 peak around maximum, 1 during transition, another at minimum), less significant with more bins Shows strongest flares right before phase minimum though.

TYC 4595-107-1 (G type): similar to BD-08 995, increase of flares right before minimum, slight (less significant) increase at maximum. (appending folded lightcurves in appendix)

V471 Tau: binary with white dwarf, most flares around white dwarf transit -> magnetic interactions likely (ref. to V471 Tau specific papers) Strongest flares also around that

HK Aqr (M dwarf): not fully trusted results, half period was detected for 2/4 lightcurves (original folding had 2 fit maxima too far away from edges, caused it to check for if half period signal was detected and use that) only full period results show overall less flares during the maxima

KOI-256 (M dwarf): similar issue as HK Aqr, in 2/7 Kepler, 2/3 TESS lightcurves, like V471 Tau binary with white dwarf, shows significant dependency on spots in with period folded results. (appending folded lightcurves in appendix) Largest flares, when period folded only, also at around 0.8π (same flare shifted to 2π in spot modulated fold), otherwise flare energies well spread.

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
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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
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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

Additional folded lightcurves

B.1 TYC 4595-107-1

Appendix C

C

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.

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Graz, May 25, 2025

Markus Ornik