Contents

Chapter 1

Application

Micro-lensing leads to an observation of several images from one object, e.g. from a quasar. For this thesis, image pairs of several epochs (observation dates) shall be studied. The aim of this thesis is the calculation of the magnitude differences between two spectra, at the continuum as well as at the line wings. The magnitude differences rise from the micro-lensing effect, but also from the lensing effect. In order to calculate all differences of each of the provided spectra at three different emission lines, an application was written with Python 3.7 and was tested on Windows10 and macOS10.14. The application includes a graphical user interface (GUI) which was developed using the library Tkinter. The emission lines, for which the micro-lensing calculations can be done with this application, are C IV (1549.1 Å), C III] (1908.7 Å) and Mg II (2798.8 Å). In order to use the application, text files which contain two columns, separated by a space are required, the first one for the wavelength and a second one for the intensity. The values of the x-axis must be in units of Å, the values of the y-axis can be in arbitrary units.

In the following, the application features are mentioned, an user guide is given as overview, a detailed description of all steps as well as a mathematical background is given. Furthermore, the code is explained, and possible code improvements are listed for this application.

Finally, the micro-lensing simulation is explained. Therefore magnification maps are generated in order to study the flux variations of the quasar, using the Inverse Polygon Mapping (IPM) method (Mediavilla et al., 2006).

1.1 Application features

The application calculates the magnitude differences between two spectra for three different emission lines, namely C IV (1549.1 Å), C III] (1908.7 Å) and Mg II (2798.8 Å). The continuum differences as well as the line wing differences can be evaluated for these emission lines. For magnitude difference

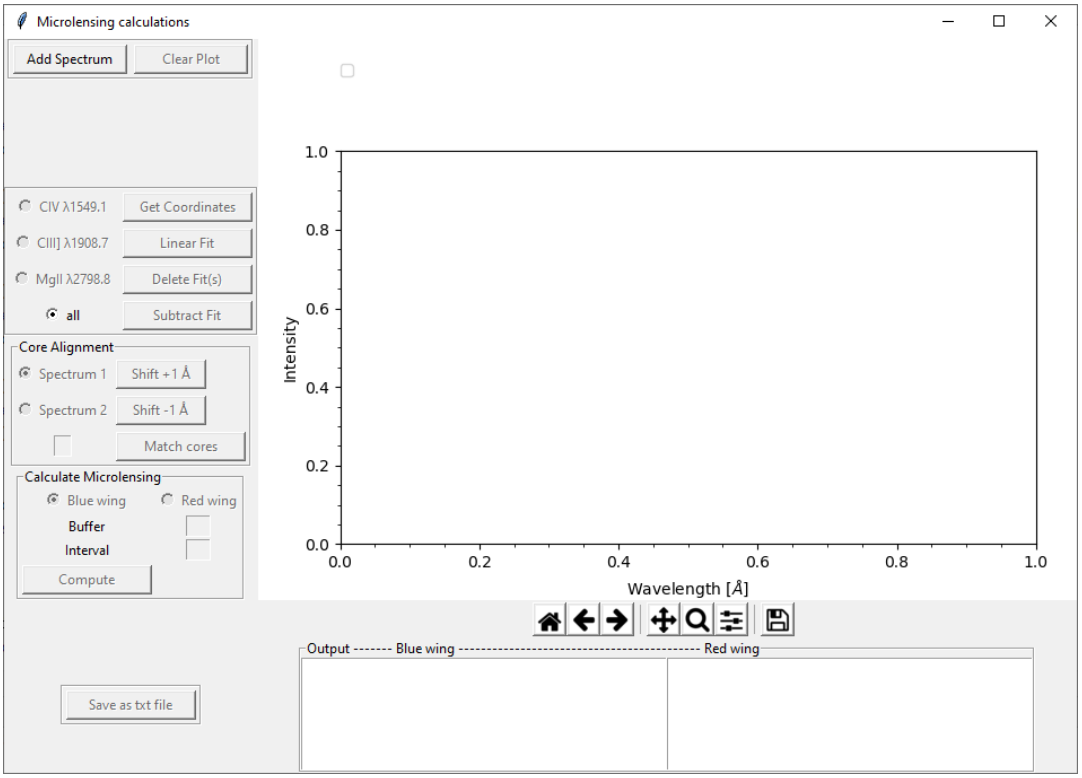

FIGURE 1.1: Application interface for the evaluation of the micro-lensing.

calculations of other emission lines, the code may be changed, as explained further below. It is possible to add more than two spectra, but the micro-lensing calculations only work for two spectra with this application.

Figure 1.1 shows the user interface. The application is split in two areas: Buttons and input fields are on the left side, the plot and the output field are on the right side. The buttons enable the user to initiate the reading, editing and calculation of the spectra. The plot shows the chosen spectra as a function of wavelength and intensity. The plot can be zoomed in to the emission line of interest, and continua values can be obtained by clicking on the continua at the plot. Furthermore, the most important emission lines are shown by vertical lines and labelled at the top of the plot. The three lines of interest are shown as solid black lines, the other ones are dashed grey lines.

1.2 User guide

In the following, the required steps are listed in order to get an overview how to use the application. Afterwards, each step is explained and shown by an example, for which two spectra were used from the same data than used for this thesis.

1. Add two spectra.
2. Choose one emission line.
3. Get the continua coordinates.
4. Make two linear fits at the continua.
5. If necessary, delete the fits and repeat last step.
6. Subtract fits from the continua.
7. If necessary, shift spectra along the x-axis.
8. Select the line core interval for the core alignment.
9. Match the line cores.
10. Select intervals for the micro-lensing calculations.
11. Calculate magnitude differences due to micro-lensing.
12. Save the spectra as text file.

In order to show how to work with the application, an example is given, using one of the spectra pairs from table **??** (epoch 2016, Fian et al. in preparation).

1.2.1 Adding spectra

Figure 1.1 shows the user interface how it appears after starting the application. At the top left of the application interface, the button 'Add Spectrum' must be clicked, then an open dialog appears and a text file can be chosen. The spectrum is then plotted at the right. The wavelength lies on the x-axis in units of Å, the intensity lies on the y-axis in arbitrary units. The range of the x-axis is defined by the range of the given data. In case that the wrong spectrum was chosen from the open dialog, it can be deleted by clicking on the button 'Clear Plot'. The button 'Add Spectrum' must be clicked again to select and add a second spectrum. The window has been maximized for the purpose of a better overview of the spectra and their emission lines. Now, two spectra are plotted, as shown in figure 1.2. Both spectra show the same object, but are still quite different.

At the top of the plot, the labels of the spectra are located, as well as the labels of the most important emission lines, namely the three lines of

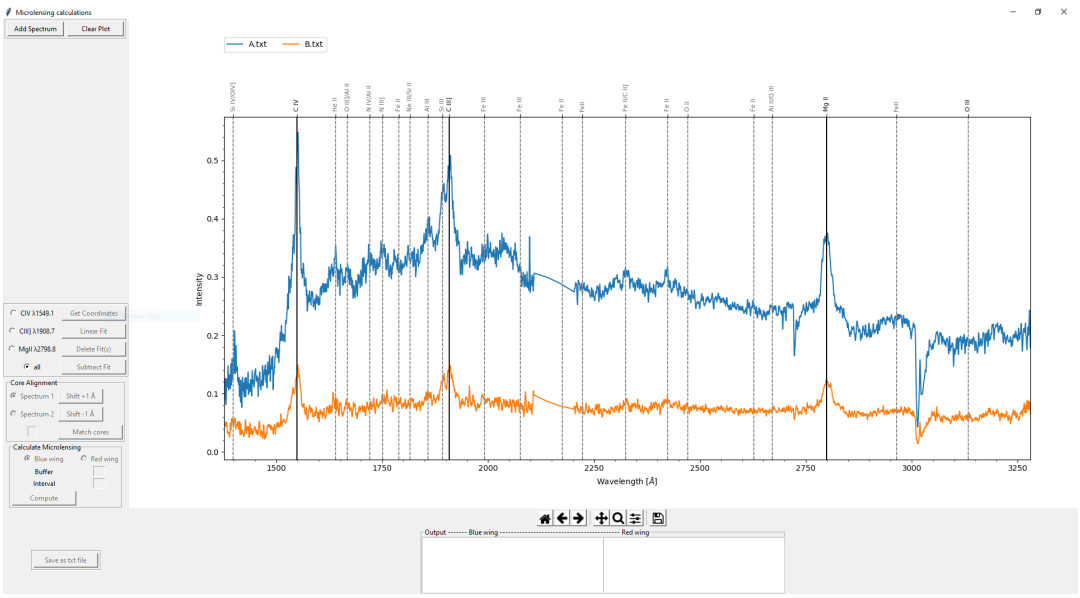

FIGURE 1.2: The application interface after adding two spectra. For this example one of the spectra were used from

interest. The thick lines show the most important emission lines, the dashed ones show other emission lines which can be also seen. A click on the button 'Clear Plot' deletes all current spectra from the plot.

Afterwards, one of two spectral lines has to be chosen for zooming in the specific line of interest, namely C IV (1549.1 Å), C III] (1908.7 Å) and Mg II (2798.8 Å). This can be done by checking one of the radio-buttons at the left. The plot now shows the chosen emission line range. One can come back to the view of the whole spectra by selecting the radio-button 'all'. However, the calculations can only be done by selecting one of the three emission lines.

1.2.2 Linear fits at the continua and fit subtraction

The next step required is to generate linear fits of the continua of the spectra. This step is necessary in order to subtract the continua from the spectra later. As one can see in figure 1.2, the continua of both spectra are neither lying on the same intensity level, nor are they lying at $y = 0$.

After checking one of the radio-buttons C IV (1549.1 Å), C III] (1908.7 Å) and Mg II (2798.8 Å), the plot shows the zoomed emission line as well as two black dotted lines at each emission line wing, which indicate the region of the continuum at the blue side of the emission line and the red side of the emission line, respectively. The situation is shown in figure 1.3. Since these two regions are a guide for finding the continuum and might be overlaid by another emission line, they must be used with care.

Next, the button 'Get Coordinates' must be clicked. One is now able to get the coordinates of the firstly loaded spectrum (which is the left one labeled in the legend). Now one has to use the mouse to define four points, by clicking two times at the left side of the spectrum in the region of the continuum, and two times at the right side of the spectrum in the region of the continuum, respectively. After clicking four times, the button 'Linear Fit' can be clicked and as a result the plot updates and the computed linear fit is plotted in addition to the two spectra. Figure 1.3 shows the user interface with both spectra plotted as well as both linear fits.

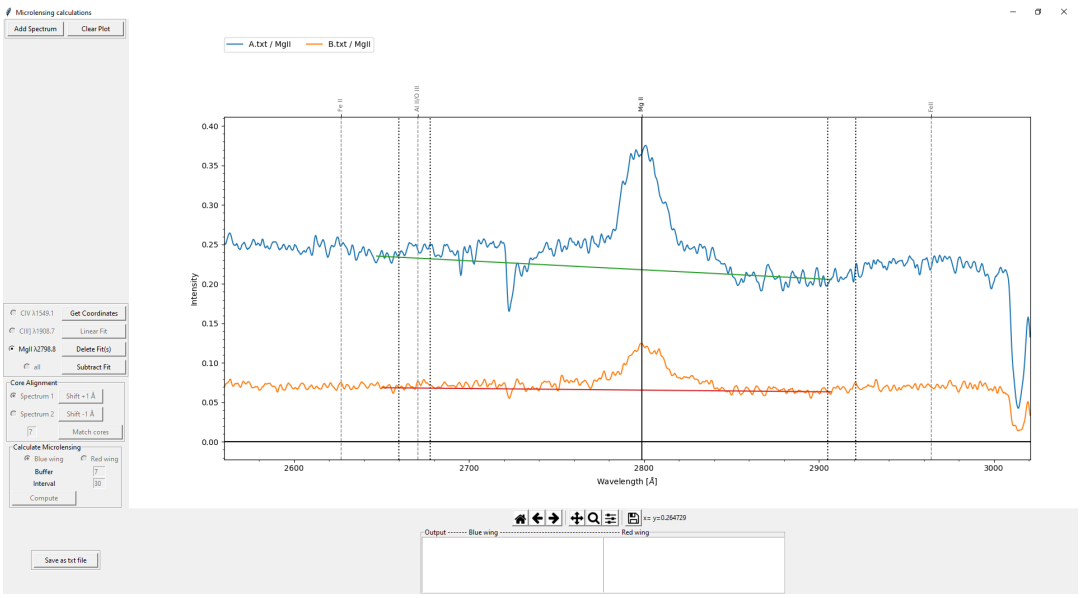

FIGURE 1.3: The two lines are the linear fits, which are calculated and plotted for each spectrum.

The averaged intensity value from two clicks on each side are taken to calculate the fit. The same procedure has to be done for the second spectrum. The continua of the spectra are now lying at $y = 0$. If the linear fit or both fits, respectively, are not adequate, one can delete the fit(s), by clicking on the button 'Delete Fit(s)'. The fits are then deleted and one can start again by clicking on the button 'Get Coordinates'. After making a fit, the mean continuum values are printed in the console for the current spectrum. These values are of interest later in order to compute the magnitude differences in the continua and can therefore be neglected at this point. Finally, a click on the button 'Subtract Fit' leads to the subtraction of both fits from the spectra. The spectra are now normalized, which can be seen in figure 1.4.

It is recommended to make the fits according to some fitting guides: If there is a bump in the region of the continuum, this could be another emission line and not the continuum. In this case, the mouse-clicking should be

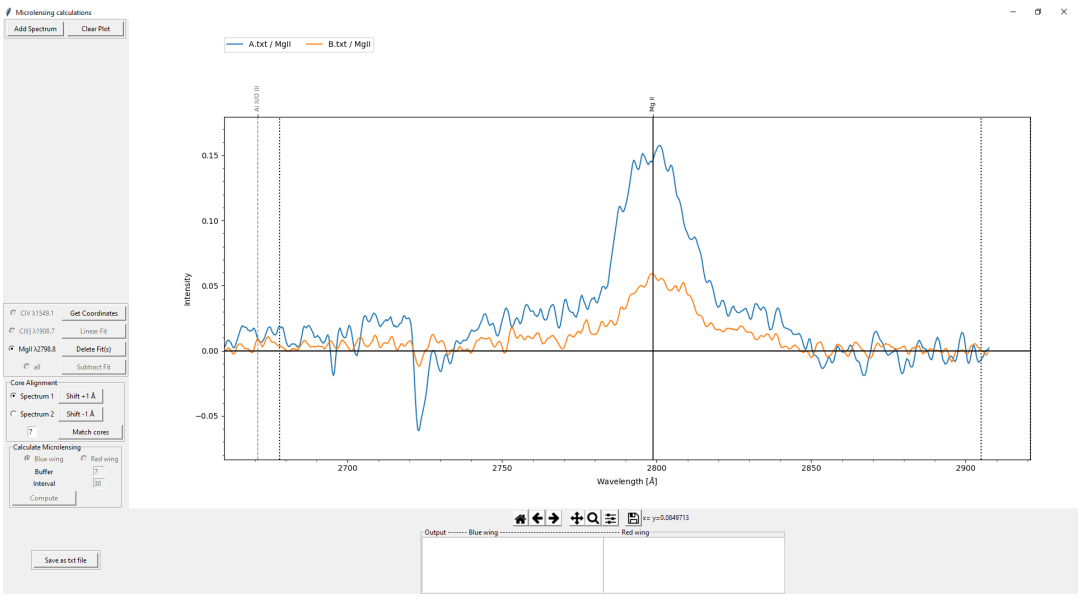

FIGURE 1.4: The linear fits are subtracted from each of the spectra. The continua lie at $y = 0$.

done right beside of this line. The first spectrum should be fitted at the same area at the continuum than the second spectrum, and the interval between two clicks at each emission line side should be of the same length for both spectra. After the subtraction of the fits, the continua of both spectra should overlap as well as possible. Furthermore, all epochs should be fitted at the same area in the region of the continuum. By clicking on the 'Save' icon, located below the plot, the spectra and the two linear fits can be saved in order to remember later where the continua were fitted. As a guideline, the continua should lie at $y = 0$ and the wings should not lie under $y = 0$, after the subtraction of the fits.

Mean continua and line cores

The line core values of both spectra are printed in the console right after zooming into an emission line. Also the standard deviations of the mean core values are printed. The mean line core values are computed by calculating the mean of all values within the range of 7 Å. This range is fixed and can be changed by changing the value within the Python code itself, which is explained more precisely later.

Furthermore, the mean continuum values of the blue and red side of the emission lines are printed on the console for each of both spectra as well, right after the linear fits were plotted. Additionally, the standard deviations of the mean values are also printed on the console. The output values are

rounded to two decimal places. The mean continuum values are computed by calculating the mean of all values within the range of the two points, which were defined before by clicking into the plot, for each side of the line and for each spectrum.

1.2.3 Core alignment

Before one can align the spectra along the y-axis (intensity axis), the cores should overlap along the x-axis. It is possible that the one line core or both line cores don't lie at the vertical line drawn at the emission line of interest. In this case, the spectra are shifted along the x-axis, which implies that the line cores of the spectra don't coincide with the literature values. For that reason it is required to shift one spectrum or even both along the x-axis. With the radio-buttons 'Spectrum 1' and 'Spectrum 2', one can select the spectrum which should be shifted. The buttons 'Shift + 1 Å' and 'Shift - 1 Å' provide a shift of 1 Å in each direction along the x-axis. As a result, both spectra should overlap at the cores as well as at the wings.

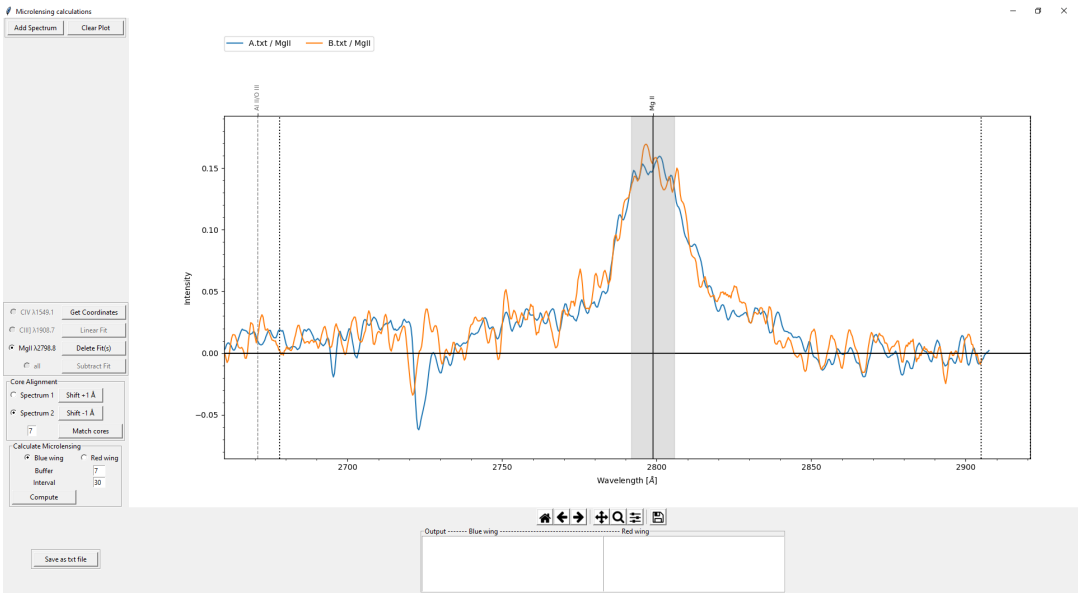

FIGURE 1.5: The spectra are shifted and the line cores are matched. The grey shaded area indicates the area of the line cores.

The core alignment at the y-axis can be accomplished by clicking on the button 'Match cores'. The application now calculates the mean intensity value of both spectra within a specific interval. The interval can be selected by filling in the input box at the left side of the button 'Match Cores'. The unit of the value in the input box is Å. After clicking on the button 'Match

cores', the range of this value is plotted as a grey shade, which can be seen in figure 1.5. The spectra now overlap along the y-axis, and the both line cores have approximately the same intensity level.

The core alignment is made by the following calculations: The mean intensity of the values within the grey shade of the first spectrum is calculated, and the same calculation is done for the second spectrum. The first spectrum's mean core intensity is then divided by the mean core intensity of the second spectrum. This gives the multiplication factor which can now be multiplied by both spectra. Finally, both spectra are matched and ready for the magnitude differences calculations.

1.2.4 Magnitude differences in the wings

Finally, the magnitude differences between the wings can be calculated. The required buttons can be found within the frame 'Calculate Microlensing', which is located at the left side of the application, below the frame 'Core Alignment'. At first, the red or blue wing must be chosen by selecting one of the corresponding radio-buttons 'Blue Wing' and 'Red Wing', respectively. The input field 'Interval' defines the region for which the micro-lensing should be calculated. The input field 'Buffer' defines the interval between the core interval (which was defined to match the cores) and the beginning of wing interval for which the micro-lensing calculations should be done. All input fields are in units of Å. The input fields 'Buffer' and 'Interval' correspond to the chosen radio-button, that means that the input fields can contain different values for each wing and the button 'Compute' must also be clicked for every wing separately. With these two selections the interval can be shifted and enlarged or scaled-down, respectively, for each the blue and red side of the emission line. After clicking on the button 'Compute', the intervals are shaded in blue and red at the plot, for each side of the emission lines, as shown in figure 1.6.

The magnitude differences, the standard deviations as well as the signal-to-noise ratios are output in the output field, located at the bottom right of the application, for the blue and red wing, respectively.

1.2.5 Different velocity bins

By choosing two bins on each side of the emission line, one can obtain the magnitude differences for different velocity regions. Figure 1.7 shows the two bins with an interval of 15Å each and a buffer of 7Å. Figure 1.8 shows

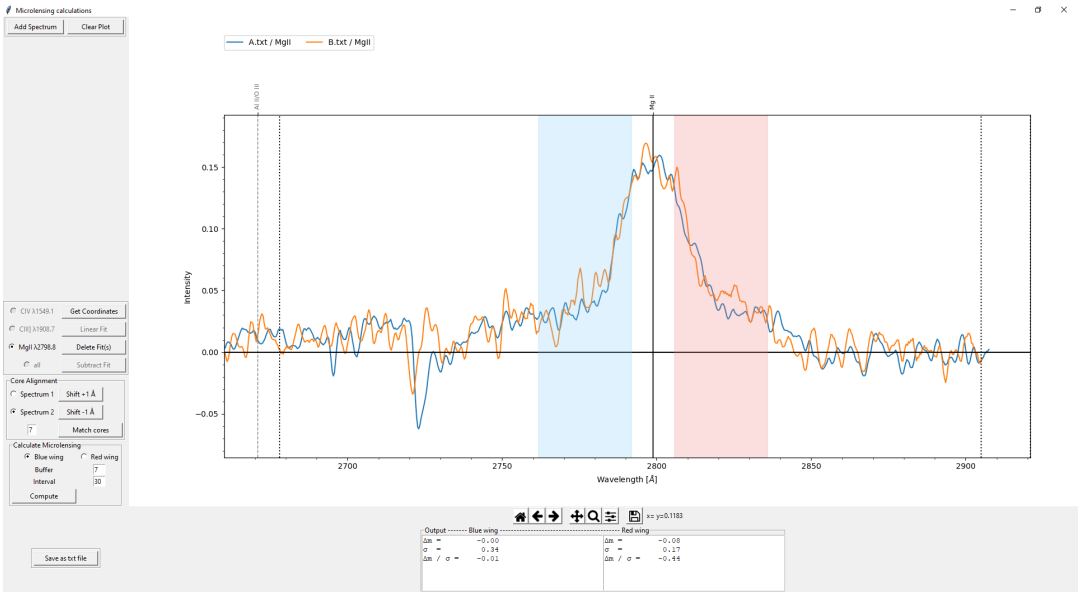

FIGURE 1.6: Wing regions for which the magnitude differences are calculated. The wing region on the blue side of the emission line is shaded in blue, the wing region on the red side is shaded in red, respectively. In between, the core region is located. Below, the output field shows the micro-lensing results for the line wings.

two bins with an interval of 15Å each and a buffer of 22Å. The two intervals at each emission line side adjoin to each other, which results in an overall interval of 30Å at each side. The bins near the core are called the 'inner bins' (blue bin 1, red bin 1), the bins near the continua are the 'outer bins' (blue bin 2, red bin 2). The intervals which are chosen here are default values and suitable for this example, they must be adapted for every emission line.

1.2.6 Saving data

The button 'Save as txt file' can be found at the bottom left of the application. By clicking on the button, a file dialog opens and the two edited spectra can be saved in a text file. The file has four columns, the first two columns contain the x-values and y-values of the first spectrum, the second two columns the x-values and y-values of the second spectrum, respectively. The range of the saved spectra conforms with the range of the plotted spectra, which always includes the current emission line only.

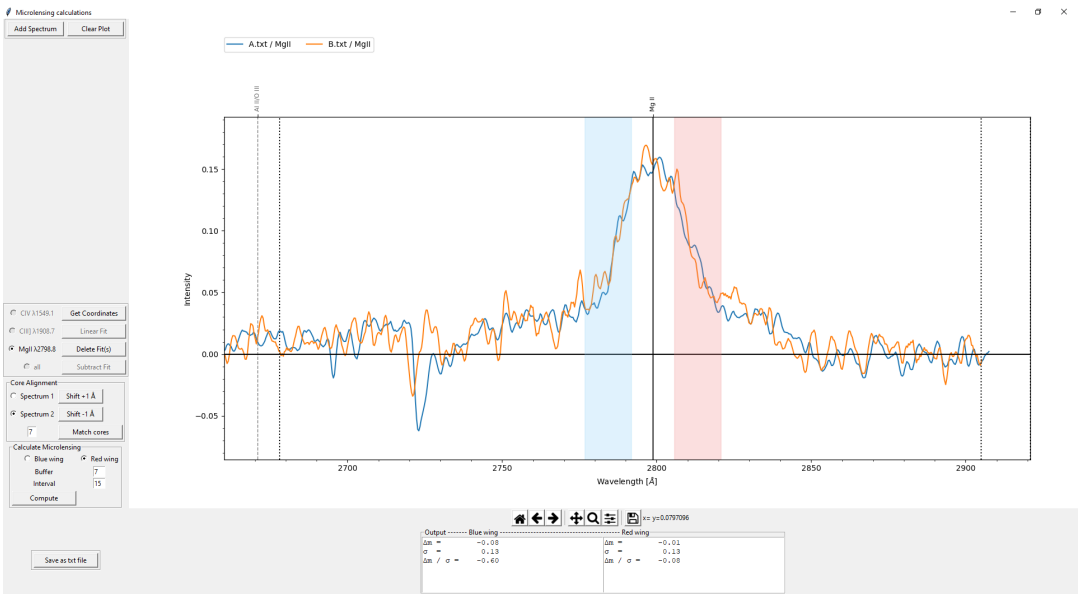

FIGURE 1.7: Spectra with the two inner bins, shaded in blue and red, respectively. The bins have each an interval of 15Å.

1.3 Python Code

The application was written using Python 3.7. The GUI (graphical user interface) package Tkinter was used. The code was written in an object-oriented style. In the following, the code is shortly explained to provide a better understanding. The class 'Program' is the main class. This is where the user interface frames and their elements are defined as well as some variables are set. The literature values of the emission lines are set. If one wants to analyse other lines than the used ones for this thesis, one has to replace the variables 'lines_c4', 'lines_c3' and 'lines_mg2', as well as all corresponding variables (core values, labels). The changes should be made very carefully in order not to disregard any variables.

The class 'GetData' provides the ability of reading of the data files.

The class 'Plot' handles the plot and all corresponding functionalities. The plotting frame is defined, as well as all emission line labels and their dotted and dashed lines. The method 'x_range() provides the zoom of the plot to one of the three requested emission line (C III, C IV or Mg II). Within this method, the mean line core values are computed as well, by calculating the mean value within an interval of 7 Å, centered at the y-value with the highest intensity. This interval can be changed by changing the variables 'x-upper' and 'x-lower', respectively.

The class 'MouseLocation' handles the click events. If one presses the button 'Get Coordinates', one has to mouse-click four times in order to get

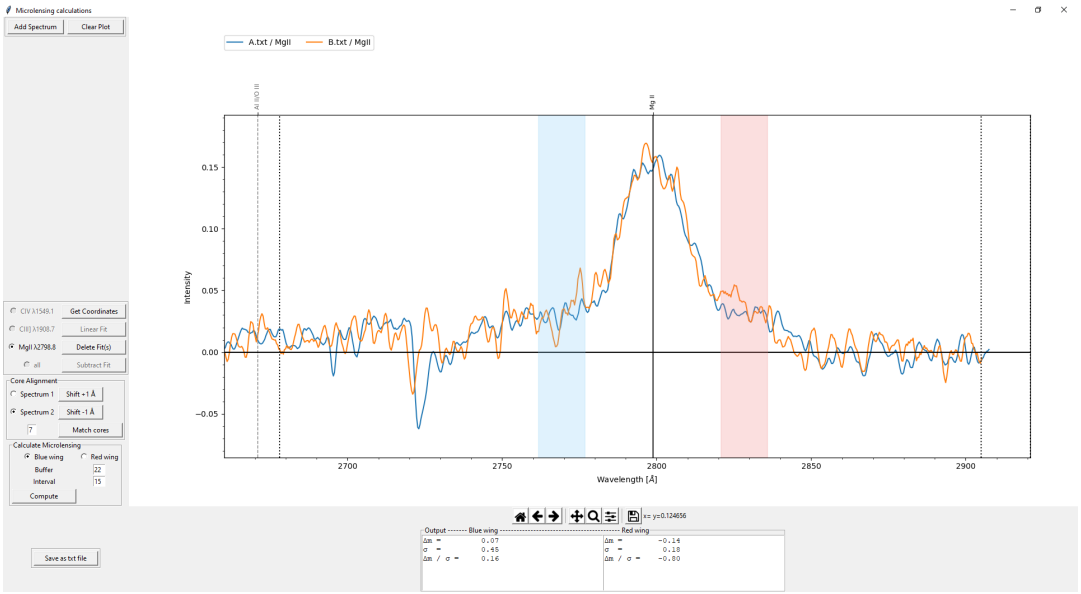

FIGURE 1.8: Spectra with the two outer bins, shaded in blue and red, respectively. The bins each have an interval of 15Å.

the four required x-values for the current spectrum.

The class 'LinearFit' calculates the fit and provides the fit deletion and the subtraction from the continuum. Furthermore, the mean continuum values and their standard deviations are calculated.

The class 'MatchCores' handles the emission line cores in order to match them. The mean intensity maxima are calculated.

The class 'Microlensing' is used for the interpolation of both spectra with x-values from each other spectrum. The scale is then changed from intensity to magnitude. Finally the magnitude differences are calculated for each wing, as well as their standard deviations and the signal-to-noise ratios.

The class 'Spectrum' defines the type of the data lists. Every spectrum is handled as an object with features like x- and y-values, and a name. Also the linear fits are treated as these objects for reasons of simplifications.