Spectral Data Reduction

for

Amateur Astronomers

Task-oriented Tutorial

with Freeware Programs

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Content

1   Introduction

It exists a large variety of programs for the data reduction of recorded spectra, as well as for the generation, calibration and analysis of spectral profiles. [1] provides an overview to what is presently available in the professional and amateur sector.

The main goal here is to provide a task-oriented guide, optimized for the most important spectroscopic applications and involving several programs. Thus this description is to be understood just as a supplement to the program-specific manuals and should further be comprehensible particularly for amateurs.

The stepwise processing of spectroscopic data reduction, as well as the generation and calibration of an intensity profile, are demonstrated here with IRIS and Visual Spec. Further for some auxiliary functions, ISIS and Fitswork are used. The described processes are restricted to those which the author applies himself but never claiming to be the most optimal options within these extensive and very well-documented programs. This document also reflects the specific experiences gained by the numerous recordings for the spectral atlas [2] and is also intended as a practical supplement to the books:

– Marc F.M. Trypsteen, Richard Walker: *Spectroscopy for Amateur Astronomers, Recording, Processing, Analysis and Interpretation* [1]

– Richard Walker: *Spectral Atlas for Amateur Astronomers, A Guide to the Spectra of Astronomical Objects and Terrestrial Light Sources* [2].

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Special thanks to Valérie Desnoux and Christian Built, but also to Jens Dierks, the author of Fitswork, for writing these fine programs and providing them as a freeware. A real door opener to the world of spectroscopy for a fast growing number of interested amateur astronomers around the globe!

2   Preliminary Remarks and Applied Programs

2.1   Recording and Processing of Spectral Pictures

The Freeware *IRIS* Version 5.59 [10] is applied here for the processing of the spectral image and Vspec Version 4.2.6 [11] for the subsequent generation and evaluation of the spectral profile. The displayed spectra were obtained with the DADOS slit spectrograph from Baader Planetarium and recorded with the Atik 314L +. The processing of "Flats" was generally omitted [1].

2.2   Applied Programs

Both, IRIS and Vspec, are running under all versions up to Windows 10 in the languages French or English (2017). With both programs, different ways are often leading to comparable results. For the described spectroscopic applications, only a small fraction of the entire IRIS and Vspec functions are needed. Therefore it is strongly recommended to consult also the authors' manuals and tutorials [10], [11]. IRIS for example, provides abbreviated methods enabling for a whole series of spectral recordings the simultaneous extraction of the sky background in a single step. The author however prefers to perform a stepwise reduction of the individual recordings and to combine this way a quality inspection and selection of the images to be evaluated.

Furthermore, provided by the ISIS software, the databases of the standard stars for the relative, spectrometric flux calibration are used here. In addition, Fitswork is applied to convert the RAW files generated by DSLR color cameras into the black and white Fits format.

2.3   IRIS

The freeware IRIS was developed by Christian Buil as a quite extensive, astronomical image processing program. Here just a small part of the special division for spectra-processing is applied.

http://www.astrosurf.com/buil/us/iris/iris.htm

Some steps for processing the spectral recordings must be entered as so called "commands", via a "console" with correct syntax. Anyway, in more recent IRIS versions, many functions, here still described as "Commands", are now implemented as menu items. This "console" can be activated with the icon ⊞. Each command line must start with > and finally be confirmed by "Enter". Since IRIS, in the current version 5.59, knows neither a close nor a clear command, it has been proven to restart the program with *exit* before loading a new image.

It is absolutely mandatory to define a *default path* for the *working directory* in *Program Files/Settings/Working path*. Otherwise, without any error messages, various IRIS commands will not be executed! For download of IRIS see [10].

2.4   Visual Spec (Vspec)

The freeware Vspec (Visual Spec) [11] was developed by Valérie Desnoux mainly for the generation and analysis of spectral profiles, which are based here on spectral stripes, processed by IRIS. The procedures described here can all be accessed by conventional menu items in the title bar. Anyway as IRIS, also Vspec provides a console mode. The installation of the program must be carried out exactly according to the instructions of the homepage and the download address by Valérie Desnoux:

http://www.astrosurf.com/vdesnoux/

With some versions of Windows it has also been proven to install and open the program as *system administrator*, to avoid DLL and other error messages. The analysis tools, implemented in Vspec, e.g. lists with ions and elements, apply Angstroms [Å] as wavelength unit. If these tools are not applied, the spectra may also be calibrated in any other units such as [nm] or [eV].

It is further advisable to define the same working directory for Visual Spec *(File/Options/Preferences)* as for IRIS.

2.5 ISIS

ISIS Version 5.8.0 [10] by Christian Buil is a kind of "synthesis" of the spectroscopic functions of IRIS and Visual Spec, including many of the features described here. However, the author prefers the separate processing with IRIS and Vspec, because he considers this path to be more flexible with regard to the parameters to be set and the possible processing options. The procedures described below use in just one case a data base, which can be found in the root directory of ISIS, containing numerous standard stars for the flux calibration.

Especially for owners of Shelyak spectrographs and those who prefer a widely automated processing, it is worth considering ISIS for the general data reduction.

http://www.astrosurf.com/buil/isis/isis_en.htm

2.6 Fitswork

Fitswork by Jens Dierks (here Version 447) is a well-known freeware for the processing of astronomical images. For the processing of RAW files described later (e.g. taken with Canon color cameras), the Zip folder dcrawfw1477.zip, must be copied in to the program folder of Fitswork and finally unzipped.

Already at the beginning Fitswork has to be downloaded in the desired language. A subsequent language change seems not to be possible.

http://www.fitswork.de/software/

2.7 Further Programs for Data Reduction

In chap. 15, but also in [1], other programs can be found which are successfully applied in the amateur- and the professional field.

# 3   Processing of Spectral Images with IRIS

3.1   Preliminary Remarks

- The recorded spectral images must first be processed with IRIS, so Visual spec can later generate an intensity profile.

- If the wavelength is calibrated with a light source, the recordings, both of the calibration and the object spectrum, must be processed with exactly the same steps and parameters. This applies first of all to the Y-values of the spectral strip position (exact position and width of the marking frame)!

- The following descriptions assume that the raw images have been taken with a Monochrome camera in Fits format and have already been edited with any Darks and possibly Flats. In chap. 3.5 a possible way is presented how to convert Fitswork RAW files, taken with color cameras, for processing with IRIS.

- The mounting angle of the camera should be chosen so that the recorded spectral strip runs already horizontal and a subsequent, software-based correction of the angle is unnecessary.

3.2   1D Spectrum Generated from a Single Spectral Recording

If just a single spectral image of a bright object was taken, the following steps apply:

1. Copy the Fits file of the image to be processed with *„file/load"* into the working directory of IRIS.
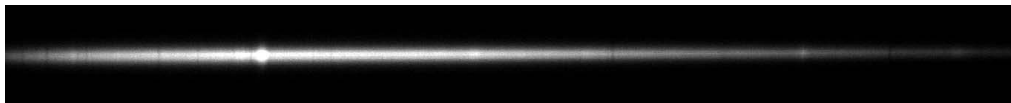
   Note: For most astronomical cameras it is the *fit* format. Often, however, other formats are used. If necessary, this can be determined by tests. It may be necessary to change the FITS file type from (*.fit, *.fits) to (*.fts)!

2. If the loaded image is exposed to short, the brightness can be increased with the upper threshold slider in the popup menu (this has no influence on the final result).

   Note: In the lower right corner of the screen, the coordinates (X, Y) and the pixel intensity (I) of the cursor position are displayed. The highest intensity value (I) in the stripe may reach *at mos*t 2/3 of the full saturation, otherwise artifacts may show up.

3. Subtract the sky background with the Command *>l_sky3*.

4. In the output window follows the request *„select 4 points"*. To mark the reference zones click each two points, slightly above and below the spectral stripe. With the final click on the fourth point, the subtraction instantly takes place.
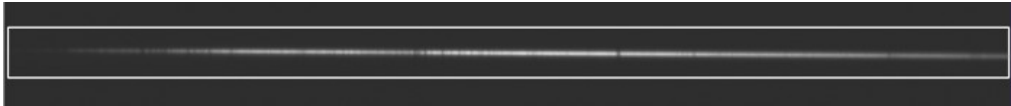

5. Remaining hot pixels or cosmics within the stripe area, can be framed with the cursor and removed with the Command   *>max X*. X is the estimated maximum number of concerned pixels.
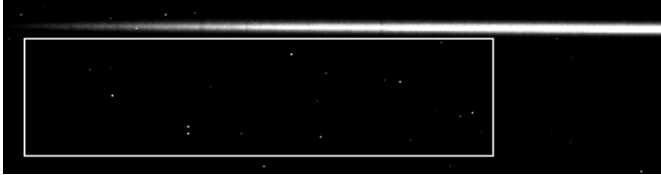
Note: Hot pixels *within* the spectral strip must be marked very closely by framing with the cursor and individually removed with >*max 1*

6. Mark the "cleaned" spectral stripe by framing:

Note: If subsequently a spectrum of the calibration light source has to be prepared, the Y-values of the upper and lower frame edges should be noted here for later reapply.

7. Generate a 1D spectrum with *Spectro/2D -> 1D optimal addition*:

Note: To generate the resulting 1D spectrum, IRIS applies an algorithm to smooth the different brightness values in the Y-direction and to increase the height of the resulting strip to 20 pixels.

8. Save this 1D spectrum with *file/save*, at best with a descriptive name, such as *Sirius 1D.* This file will later be used to generate the intensity profile in Visual Spec.

9. The command> l_plot can now be applied to generate a first provisional spectral profile for a first control, which however cannot be saved and is also not suitable for further processing.
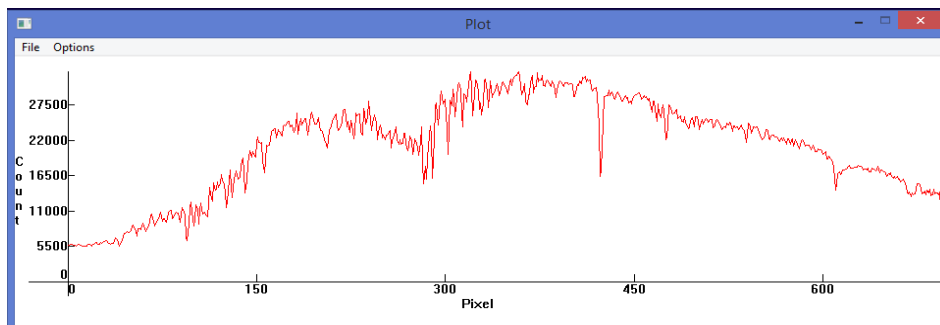
### 3.3   1D Spectrum Generated From Several Stacked Spectral Recordings

Similar to astrophotography a series of spectral recordings is stacked here. Thereby the signal-to-noise ratio SNR can significantly be improved.

1. Copy the spectral stripes for further processing in the working directory of IRIS

   Note: Each individual file must first be processed according to chap. 3.2, steps 1 – 5.

2. Rename these files and number them consecutively, from 1 to n, e.g. *castor1, castor2, castor3*. The numbering must necessarily start with 1 and no missing intermediate numbers are allowed!

3. Load the *first record* of the series (eg *castor1*) with *"file / load"* into the IRIS program.

4. Mark this stripe by framing with the cursor, comprising also the positions of the other files to be stacked.
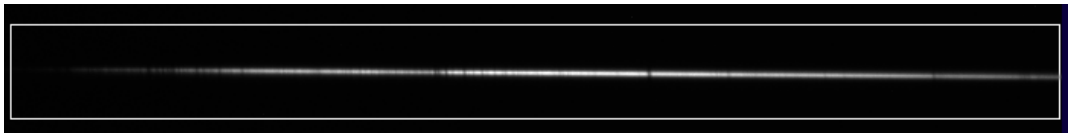
5. Start the stacking process with *"Composite of a sequence of spectra 2D -> 1D.*

6. Enter in the window "Composite" for *„Input Sequence"* the filename without a number (eg *castor*). For *„Output Sequence"* enter a different, arbitrary name or a letter like "*b*" (these generated files are later no longer needed). Enter for "*Number*" the number of recordings to be stacked (eg 3).
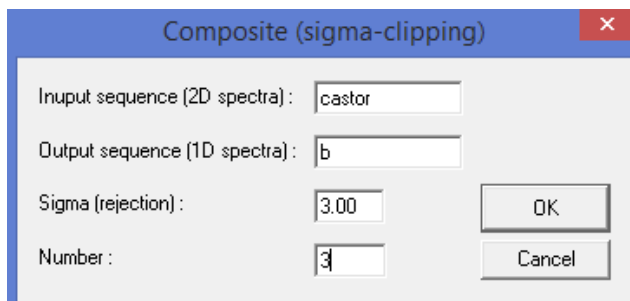
7. By clicking *OK* the Stacking of all generated 1D files is triggered

8. Save the stacked 1D Spectra with *file/save,* e.g. as *Castor1Dsum.* This file will later be used to generate the intensity profile in Visual Spec.

9. Delete in the working directory the generated but no longer needed files of the *Output sequence* (here b).

3.4   1D Spectrum Generated from 2D Appearing Objects

With the exceptions noted below, the processing runs according to sections 3.2 and 3.3. The spectra of 2D appearing light sources (daylight, sun, emission nebulae, etc.), recorded by a slit spectrograph appear here as "spectral bands" with a maximum height corresponding to the length of the slit. In such cases, a thin, "clean" strip within the desired band must

be marked with a frame - for DADOS generated by the three slits 25, 35, or 50µm.
Important: Use exactly the same marking range (Y-values) for the subsequent calibration of the object- and calibration spectra.
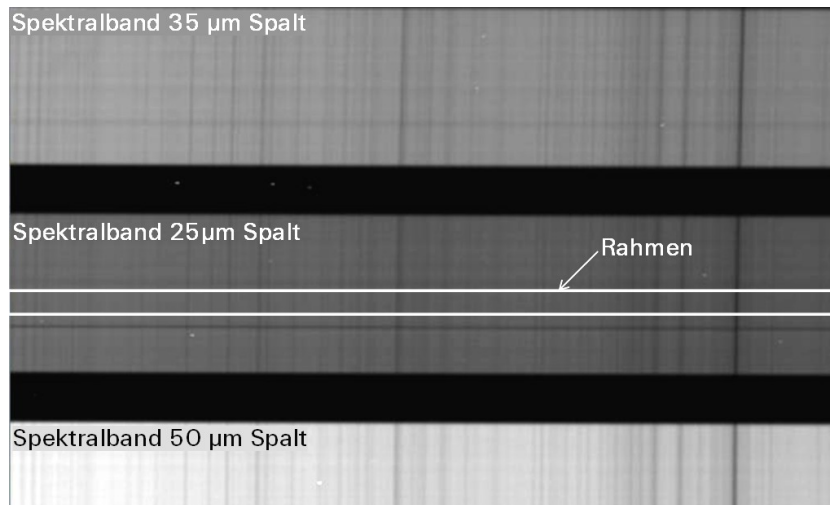
Subtraction of the sky background:

If the recorded object extends over the entire length of the slit, there is no reference left for the subtraction of the sky background with the command> *l_sky3*. In this case, immediately next to the object - and with the same exposure time - the sky background must be recorded separately and directly subtracted from the object image. However, this complicated step is required only with long exposure times, but at the latest when the emission lines of light pollution become noticeable [1]. The subtraction can be done with IRIS *(Processing / subtract to a sequence)*, but also with Fitswork.

http://www.fitswork.de/software/

3.5   Preparing of Color Images in CR2 RAW Format with Fitswork

Here just the way is shown how a single spectrum, taken with a DSRL camera in color RAW format (Canon CR2), can be converted into an IRIS-compatible fits file. The very descriptive DADOS tutorial by Bernd Koch [5] also shows how Fitswork can be used to directly stack several recordings in RAW format. Recorded with an unmodified DSLR camera, due to the filters, only a part of the spectrum of about 4000 − 7000 Å can be evaluated.
Note: This procedure also works with BMP and JPEG formats.

1. For this task the settings in Fitswork must be adjusted as follows:
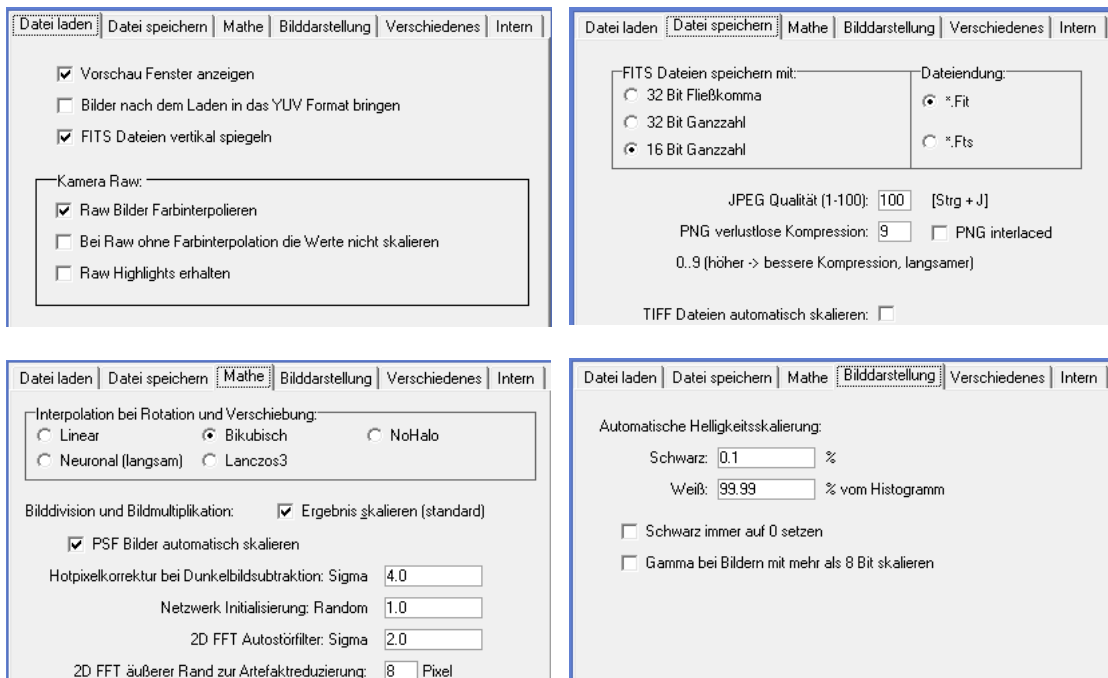
2. Load the RAW CR2 image with *File/open* in to the program

   Note: Displayed in this image are the three DADOS strips of the daylight spectrum in the orders 0, 1 (overexposed) and 2 (faint), appearing inclined at about 33° to the horizontal
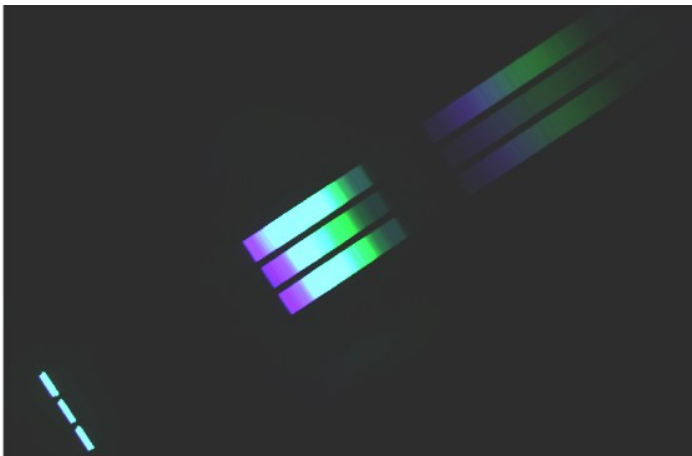
3. Rotate the spectral strips into the horizontal with *Processing/Image geometry/Rotate Image with Subsidiary Line*

4. Draw a subsidiary line with the cursor along the spectral strip
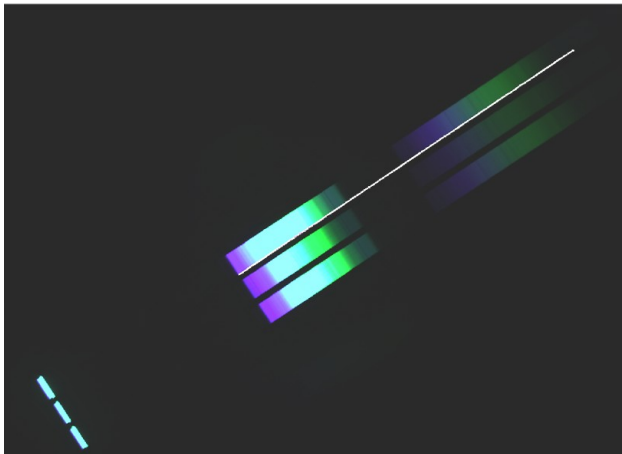
5. Confirm with Ok

6. Click the button *"Whole image"* and the spectral strips appear horizontally
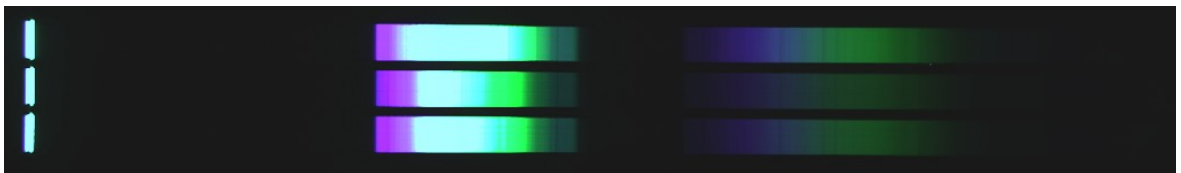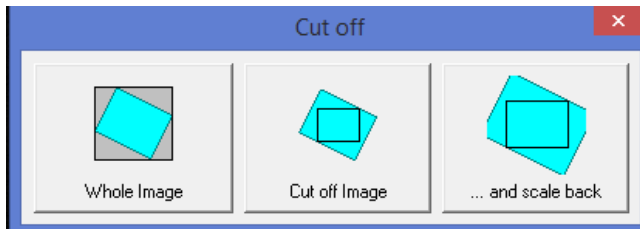
7. If several orders are shown, use the cursor to span a frame around the desired strip or the entire order (in this case upper strip of order 2).
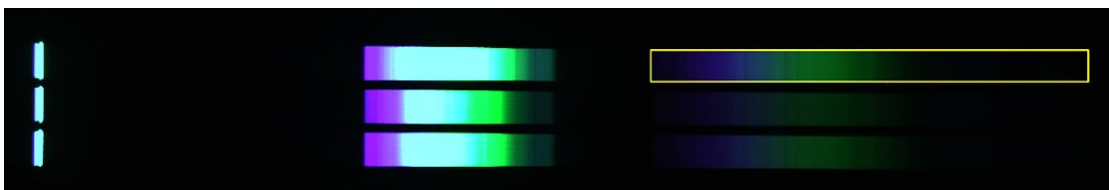
8. By click on the icon cut out the marked strip

9. Save the resulting strip with *File/Save as* e.g. *Daylight color 16 bit*

10. Convert the color strip in to b/w with *Processing/Color Image to B/W (Luminance)*

11. Save the resulting strip with *File/Save as* e.g. *Daylight mono 16 bit*

12. Further processing of the strip or the entire order in IRIS according to chap. 3.2 and ff.

3.6 Slitless Recordings with Transmission Gratings

Recordings of such spectra can be processed by IRIS, analogously to chapters 3.2 and 3.5. The best resolution is mostly achieved when the spectral strip is recorded as stretched as possible. For this purpose for the recording the image diagonal should be exploited. Finally, for the evaluation with IRIS, the strip can be moved, rotated, scaled and mirrored with the tools *Geometry / Shift, / Rotate, / Perspective adjustment, / Flip*. If a calibration is to be performed with a reference star, the orders 0 and 1 must be imaged together. For the calibration of such spectra see chap. 6.
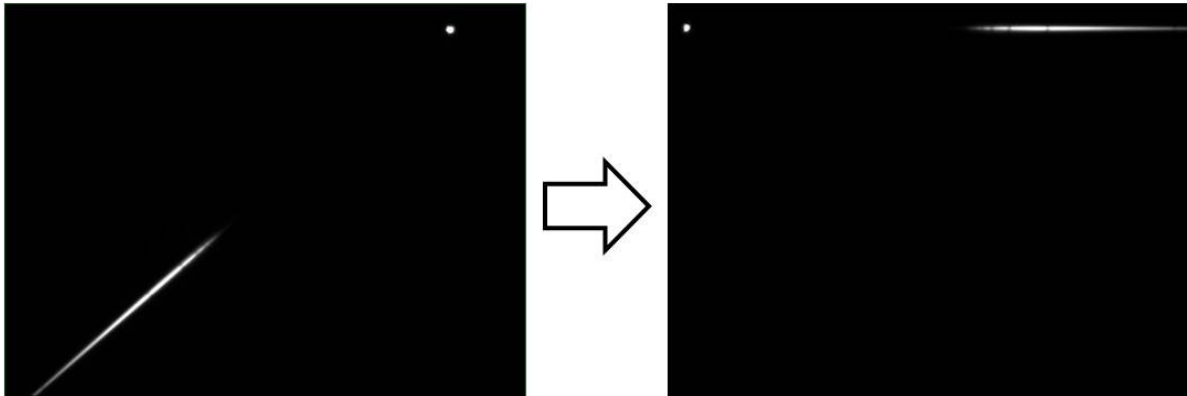
4 Generating Intensity Profiles with Visual Spec

4.1 Preliminary Remarks

With Visual Spec an intensity profile (I) is generated, plotted over the wavelength axis $(I = f(\lambda))$ and based on a 1D spectral strip, previously processed with IRIS.

- Under *Options/Preferences*, define the same working directory as in the IRIS program.

- Under *Options/Preferences/Working Directory* set the Format of Image files to *fits* and for "Profil" to *.spc*

- For heliocentric corrections, under *Options/Preferences/Position* the corresponding parameters of the observation location must be entered (coordinates in decimal degrees)

- Define further preferences as needed, e.g. *Language*.

- If in *"Open Profile"* the existing .spc files remain invisible, set the file format from *.spc* to *all*.

4.2 Generating an Intensity Profile with Visual spec

1. Load with *"Open Image"* the previously IRIS processed 1D spectral strip in to the Vspec program.

2. Generate the Raw Profile with the Icon „*Object Binning*" .
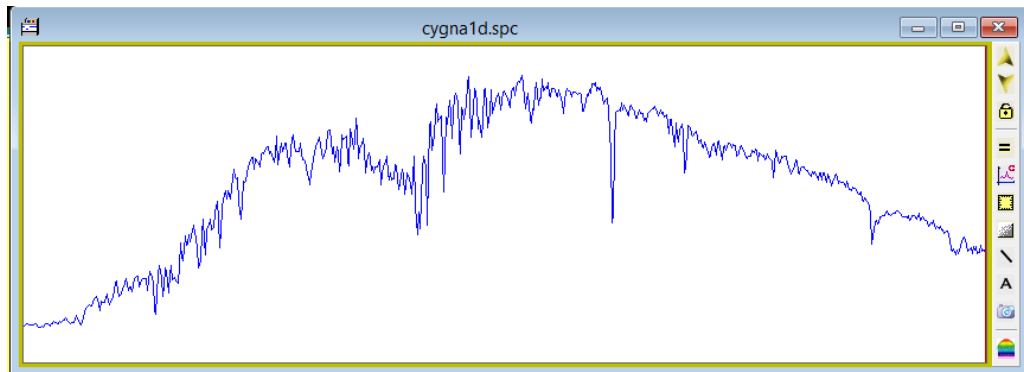
3. Save the raw profile with „*save as*" e.g. *castor.spc*.

Note: If the calibration is done with a light source, then this intensity profile has to be generated *only* for the object spectrum. The calibration process, according to chap. 5.3, applies directly the *Fits File* of the 1D calibration spectrum.

5   Wavelength Calibration with Slit Spectrographs

5.1   Preliminary Remarks

- The wavelength scale of a raw spectrum, recorded with a prism, runs strongly non-linear. But even taken with modern reflection or transmission gratings, the scale remains, albeit just slightly, nonlinear. For low requirements, Vspec allows linear calibration with only two lines. Here, however, just the only recommended, *non-linear calibration*, with at least 3 lines is described.

- If in the spectrum several well distributed lines can be undoubtedly identified, the intensity profile can be calibrated with the known rest wavelengths λ_0 (e.g., the hydrogen Balmer series). This is also the only option if the spectrum was record-ed without a slit by a transmission grating or an objective prism (chap. 6). This method is also required if, based on λ_0, unknown lines should be identified in an unshifted profile.

- Measuring redshifts in the spectrum, e.g. for determination of the radial velocity, requires the absolute calibration with the wavelengths of a light source. This is also indicated if the spectrum contains just a few known lines, e.g. with the late types of the spectral class M, or with novae and supernovae.

5.2   Non linear Calibration with at least Three Known Wavelengths

1. Load the raw profile with *„Open Profile"* into the Vspec program. (if necessary set the file format of *.spc* to *all)*

2. Start the process with *Spectrometry/Calibration multiple lines*.

   <u>Note:</u>   In the pop-up window *"Non linear calibration"*, the degree of the calibra-tion polynomial *"Degré"* can be left at the default value of 3.

3. Mark with click and drag the line profiles and type the known rest wavelengths λ_0 into the popup field. These can be found in the spectral atlas [2].

4. By confirming with *Enter* the wavelength is copied in to the window *"Non linear calibration"*.

5. Repeat steps 3. and 4. with at least two further well-distributed lines.

6. Click the *"Calcul"* button in the window *"Non linear calibra-tion"*. This starts immediately the calculation of the calibration polynomial and simultaneously calibrates the spectrum non-linearly.
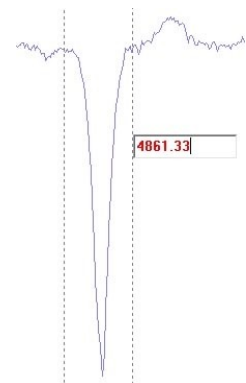
   <u>Notes:</u>

   o   In addition, a graphic shows now the course of the calibration polynomial (pic-ture on the right). Here no curved but a *straight line* must appear, otherwise cal-ibration error has happened. Invalid in-puts are announced with *"Value is not consistent"* or *"Inflection"*. In such cases Vspec marks the affected calibration point, which can then be corrected in the table.
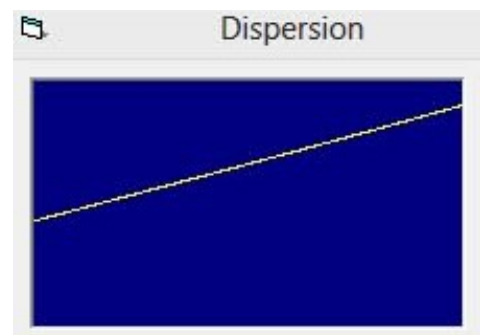
      o   The coefficients of the polynomial are displayed under *"Interpolation"*. With *Save* the corresponding equation can now be saved as *.txt* file for reapply. With *Load* and *Apply* the calibration can be transferred to another profile recorded with identical device setup. For higher standards, this method is too inaccurate, but proposed in Chap. 6 for the calibration of slitless recorded profiles.

      o   The wavelengths of the lines can also be copied from a pdf document, or other formats, with *ctrl C* and transferred in to the box with shift insert, e.g. from an atlas of calibration lines [4]. This avoids annoying transmission errors. The function *ctrl V* does not work here.

7. Close the window with *„close".*

8. Check the calibration of the profile with known lines.

9. Save the calibrated profile with *file/save* e.g. as *Siriuscalib.*

10. Clicking the yellow square 🟨 on the right edge of the box will display the scaled X and Y axes. Formatting of the graphic see chap. 8.

5.3   Non linear Calibration with Light Source

1. Load the raw profile with *„Open Profile"* into the Vspec program. (if necessary set the file format of *.spc* to *all)*

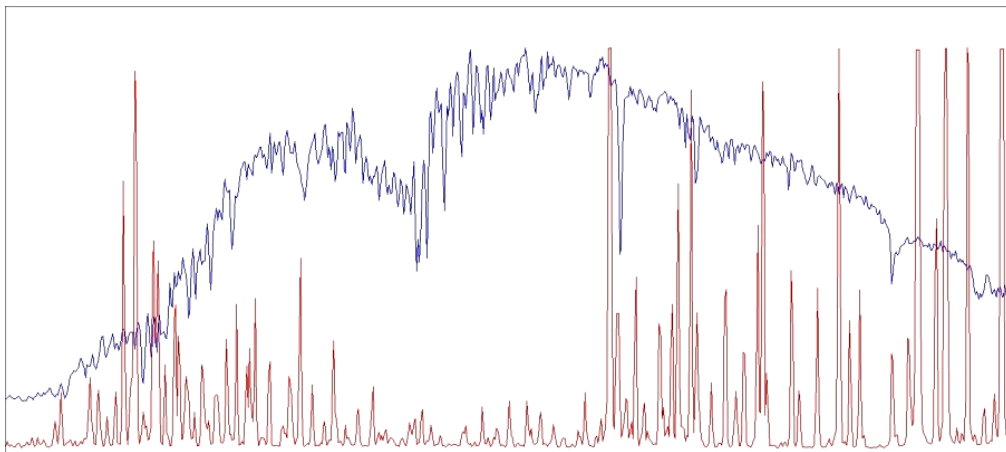2. Load with *„Open Image"* the processed 1D strip of the calibration light source

3. Start the process with clicking the Icon *Reference Binning* ▦. The generated intensity profile of the lamp spectrum appears now superimposed to the spectral profile.

4. Perform non-linear calibration with *"Spectrometry/calibration multiple lines"* analogously to Section 5.2, Steps 3 – 6. and applying well-distributed spectral lines of the calibration lamp.

   Notes:

- In the lamp spectrum no overexposed (saturated) lines must be evaluated, i.e. those with flattened peaks

- During the calibration process, the superposition of the profiles appears remaining. For better distinction it is recommendable to change the color of the calibration spectrum (in the left section of the title bar)

5. The calibration generated this way, is immediately transferred to the spectral profile *(Intensity)*.

6. Save the calibrated spectral profile (*Intensity*) of the object e.g. as *Siriuscalib.*

    Note: The still visible lamp spectrum (Ref 1) will thereby *not be saved* and must not be deleted.

7. Click on the yellow square on the right edge of the frame. The scaled X and Y axes appear. Formatting see chap. 8.

6   Wavelength Calibration with Slitless Recordings

6.1   Preliminary Remarks

In the case of profiles recorded slitless with transmission gratings or objective prisms, the main focus is here on the calibration according to chapter 5.2, which is based on the rest wavelengths of identified lines. A direct, absolute calibration of such spectra with light sources, according chap. 5.3, is not possible. Thus, a precise determination of the radial velocity is excluded.

However, thanks to the displayed order 0, for transmission gratings exist two alternatives of how to calibrate such a profile with external references. However, this requires that the orders 0 and 1 of the object spectrum must be displayed on the same picture. Further this enforces a compromise in respect of the achievable resolution, because it does not allow spreading the whole strip of just order 1 across the entire width or even in the diagonal of the image.

Order 0   Order 1

6.2   Calibration with the Dispersion and Reference to the 0th Order

This very simple, but also very inaccurate option is described in the Vspec manual, requiring the dispersion of the spectrum. This can be determined by the spectral sampling [Å/Pixel] of a calibrated reference spectrum (chap. 5.2 and 9.3) which was recorded with identical device setup. For this, e.g. a bright A-class star with a striking Balmer series can be recorded.

Starting from the common reference point *order 0*, by this very rudimentary method the calibration of the reference spectrum is just linearly transferred to the object spectrum. A typical application is the rough estimation of the redshift (z-value) of a quasar, e.g. 3C273. The following steps require a spectral 1D strip, processed according chap. 3.2.

1. Determine the dispersion of the spectrograph by the sampling of a wavelength-calibrated bright "reference" star. For the following example it yields 6.4 Å/pixel.

2. Generate the intensity profile of the object spectrum running over the orders 0 and 1
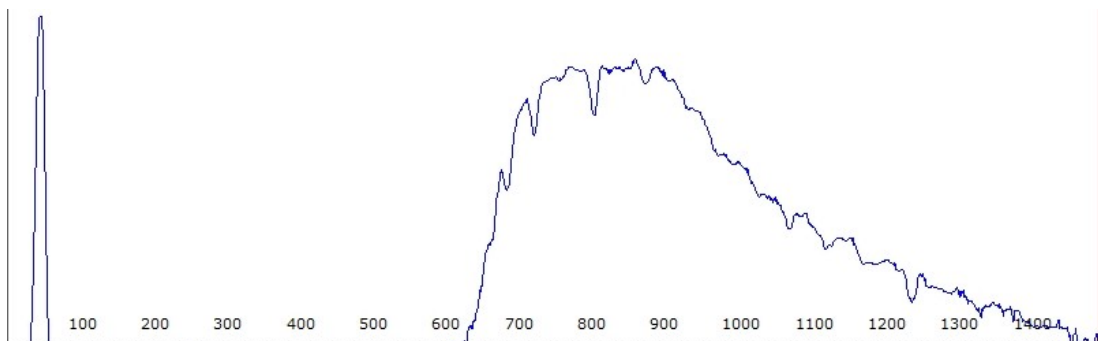
3. Mark order 0 with click and drag

4. Start the calibration process with *Spectrometry/Calibration 1 Line*

5. In the *Calibration* Window enter 0 for the *Wavelength*
    - -> Dispersion starts at Order 0.

6. For *Sampling* enter the determined value for the dispersion (here 6.4 Å/Pixel)
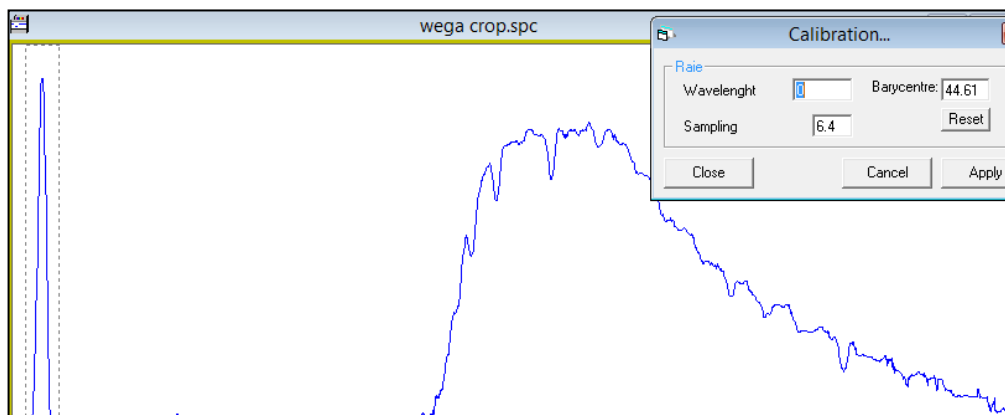
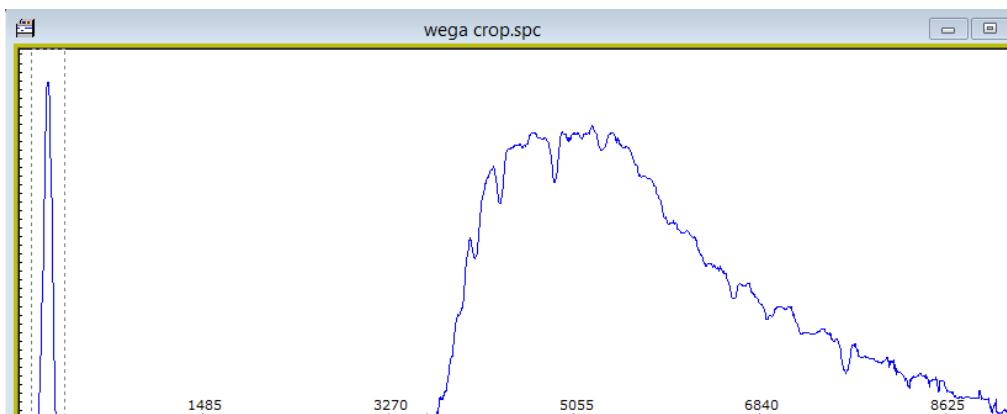7. Start the calibration process with click on *"Apply"*. Thereby the dispersion of the bright "reference" star is now linearly transferred to the object spectrum

8. Save and format the calibrated profile. Such a calibration is highly inaccurate and just applicable for very rough investigations.

6.3 Calibration with a Polynomial and Reference to the 0th Order

Calibration polynomials are usually applied for the non-linear calibration of profiles, generated by slit spectrographs (Chap. 5.2). Here an option is presented how this method, with reference to the 0th order, can be adapted to slitless applied transmission gratings. Unfortunately, the possibility to define the 0 point of the polynomial by marking the 0-th order (as in Chap. 6.2) is missing. Therefore appropriate "artifices" are necessary here. The accuracy of this method is significantly higher compared to the rough procedure according to Chap. 6.2. The following steps require a spectral 1D strip, processed according chap. 3.2.

Calibration principle

The order 0 corresponds here to the wavelength $\lambda = 0$ and forms the only common reference point for uncalibrated spectra. For this reason, the raw profiles of the "reference" star and of the object spectrum are both cropped on the left edge so they both start exactly in the apex of order 0. The object profile contains on the right side the part to be analyzed of order 1. At the right edge, the profile of the object spectrum may be maximal equal to or shorter than that of the "reference" star. With the relative simply determinable vertex of order 0, a common starting point of the polynomial for the calibration- and the object spec-

trum is forced. The following steps require a processed 1D spectral strip, according chap. 3.2.

Generation of the calibration polynomial

1. Record as a reference a qualitatively good spectrum of a bright star of spectral class A (striking H-lines) with identical device setup, and create a raw profile.

2. Crop the raw profile on the left edge in the vertex of the 0th order.

   Note: The following figure shows for Vega the way from the processed spectral strip to the raw profile, precisely cropped in the apex of the 0th order. The spectrum was recorded with the setup C8/transmission grating (200 L/mm)/Atik314L+.

Processed spectral strip

1D spectrum (IRIS)

Intensity profile (Vspec)

Intensity profile, cropped on the left edge in the apex of order 0
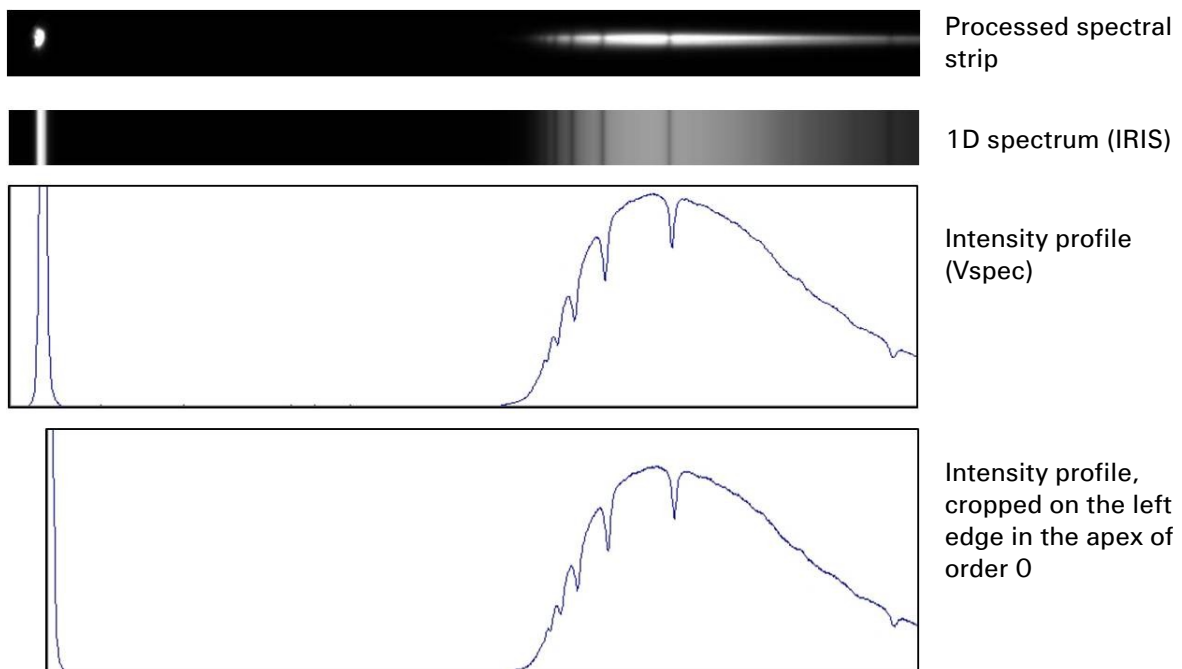
3. Calibrate the cropped raw profile nonlinearly with approx. 4 Balmer lines (chap. 5.2) including the Hα- and a short-wave (Hε or H8) absorption. The combination Hα: 6563Å, Hβ: 4861Å, Hγ: 4340Å, H8: 3888Å (possibly Hδ: 4102) has proven to be successful.

4. Start the calibration with *Calcul*

5. Check by the cursor position if the graph of the dispersion forms a straight line and if the wavelength λ at order 0 is positive.

6. If λ is negative, iteratively change the wavelength of the short-wave- and possibly also of other lines in the table by small amounts, here 3888 → 3889Å, this yielded here the new wavelength λ = +96Å at Order 0.

7. If the wavelength λ at order 0 is positive by a small amount, save the calibration polynomial with *Save.*

8. Function control of the polynomial, e.g. on an accordingly cropped raw profile

    Notes: The exclusive concentration of the calibration lines in the right-hand part of such spectra causes the relatively large deviations of the wavelength at order 0. This process therefore often requires several trials. If the wavelength λ at the order 0 is negative, the spectrum can be calibrated, but the polynomial can no longer be applied to other profiles (error message).

Calibrate the spectrum with a polynomial

The still limited accuracy of this calibration procedure allows here to reapply a proven calibration polynomial also for later sessions, if the same device setup is applied. This way the calibration of a new cropped profile gets very simple:

1. Load the accordingly cropped raw profile with „*Open Profile*" into the program. (if necessary set the file format from *.spc* to *all)*

2. Start the process with *Spectrometry/Calibration multiple lines*

3. Load in the lower part of the window *"Equation"* the previously stored calibration polynomial with *Load*:

4. Start the calibration with *Apply Eq*
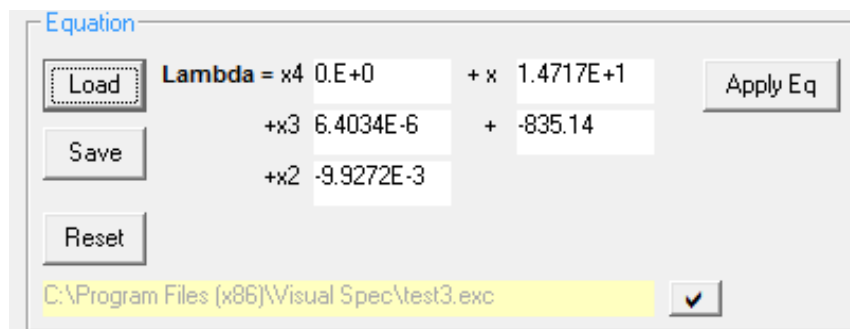
7   Calibration and Normalization of the Intensity

7.1   Preliminary Remarks

The calibration of the spectral flux density, hereafter called intensity "I" or flux calibration is much more complex compared to the wavelength λ. In addition, there are several, different options, which must be correctly chosen according to the task. For an appropriate decision support see [1].

The intensity profile of the recorded raw profile (pseudo-continuum) appears to be strongly deformed, mainly due to instrument influences, but also caused by scattering effects in interstellar space and in the earth's atmosphere. This continuum course is therefore unusable and must, together with the embedded spectral lines, be proportionally scaled to a new level. For the theoretical principles see [1].

7.2   Rectification of the Continuum Intensity

Here the intensity profile is removed from the spectral profile, and its course gets rectified. This is done by dividing the raw profile by the fit of its own continuum course. This results in a straightened, horizontal profile of the profile. Even in the professional field this simple calibration is adequate for most applications [1].

1. Load the wavelength-calibrated raw profile with „*File/Open Profile*" into the Vspec program (if necessary set the file format from *.spc* to *all).*

2. Start the process by „*Radiometry/Compute Continuum*"

3. On the new appearing toolbar, press the icon for point editing

4. Mark points with the cursor by clicking on the the now colored appearing continuum curve, whereby spectral lines must be skipped! A cross can only be set if the hand symbol of the cursor changes to the arrow display . In the case of a simple course of the continuum, an alternative to the steps 2 – 5, by *"Radiometry/Automatic Continuum"*, can be attempted.

5. Generate a fit to the continuum by clicking on the Execute icon . This continuum fit is now called *"Fit Intensity"*.

6. If the curve looks similar to the example below, press the OK button on the popup slider. If the smoothed polynomial fit (now appearing "orange") is still too "jumpy", it must be further smoothed with the pop-up slider. In stubborn cases even step 4 should be repeated. In order to achieve a visible effect (depending on the course of the curve) a two- up to a maximal five digits figure (for example 20,000) must be entered in the lower window and possibly even the x10 field must be ticked.
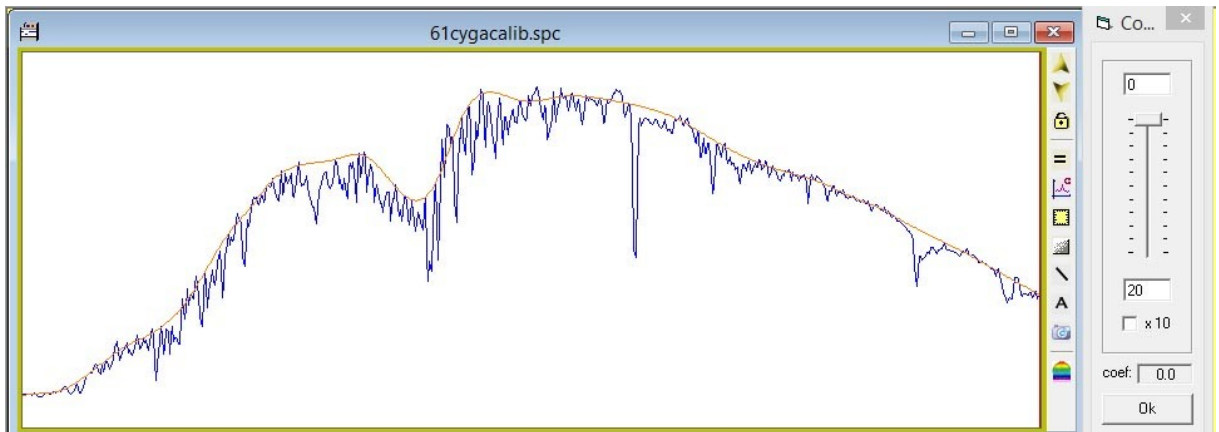
Note: With the following steps 7 – 11 the spectral profile *"Intensity"* is divided by the continuum fit *"Fit Intensity"*:

7. Delete all profiles in the window with the icon *"Erase"*

8. Select *"Intensity"* profile (window on the left edge of the header)
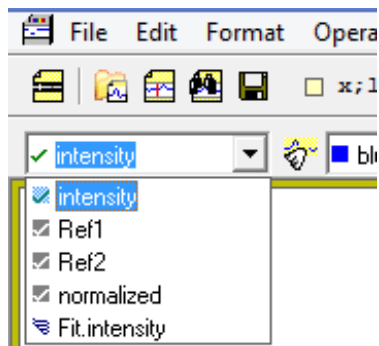
9. Click *Operations/Divide* Profile

10. In the popup window *"Selection"* activate *"Fit Intensity"* as divisor
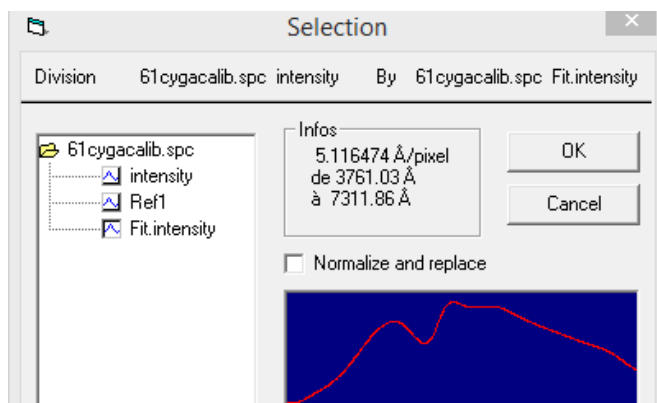
11. Confirm with OK. The rectified, continuum-adjusted profile, appears now super-posed and in green color with the name *"Division"*.

12. Click the *„Replace"* Icon

13. Mark „Intensité"

14. Confirm with *OK*

15. The adjusted profile appears now with the name "Intensity" and can be saved under a changed name.

7.3 Normalize the Intensity to a Continuum Section

After rectifying the profile according to 7.2, the intensity axis appears scaled with up to 6-digit numbers, which were derived by Vspec from the ADU (Analog Digital Units) of the raw profile. This scaling is mostly unusable and the rectified new continuum level is therefore mostly set to Ic = 1, i.e. normalized to unity.
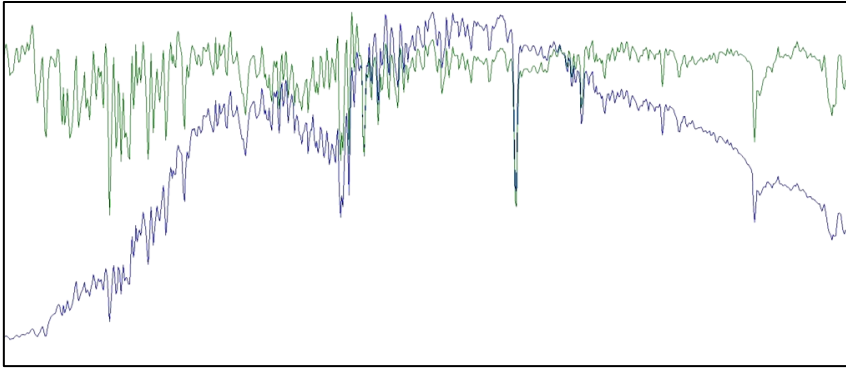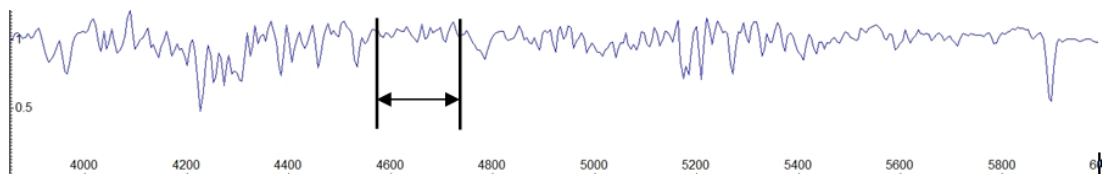
1. Mark with the cursor a representative appearing section with very few spectral lines

2. Normalize this section with the icon to 1. The continuum level has now the intensity Ic = 1. This step is e.g. necessary to determine the equivalent value EW of a spectral line.

7.4 Normalize the Intensity to the Continuum Peak

In special cases it may make sense to define the maximum peak intensity of the continuum course I_{max} exactly as 1:

1. Load the wavelength-calibrated raw profile with *„File/Open Profile"* into the Vspec program (if necessary set the file format from *.spc* to *all).*

2. Use the cursor to move to the point of highest intensity I_{max} in the profile and read off and note the intensity value I in the yellow window of the toolbar

3. Click *"Operations/Operations with values"*

4. Click *Division* in the Popup menu and enter the maximum intensity value I_{max} in the parameter field.

5. Click *Apply* and then *close*. All y-values of the curve are now divided by the maximum peak intensity, i.e. the intensity curve moves now between 0 and a maximum of 1.

7.5   Relative Flux Calibration by a Synthetic Continuum

The goal of this simplistic method is a <u>very rough approximation</u> of the recorded pseudo continuum to the *original*, and therefore *unreddened* continuum course of a recorded star. The intensities of the recorded spectral lines are scaled directly to the synthetically generated continuum course of an interstellar *unreddened star model*, as far as possible of the same spectral class. For theoretical aspects of this type of calibration, see [1].

1. Load the wavelength-calibrated raw profile with *„File/Open Profile"* into the Vspec program (if necessary set the file format from *.spc* to *all).*

2. Create a continuum fit to the Intensity profile, analogously to chap. 7.2, steps 2 − 6. This new curve is named "Fit.Intensity".
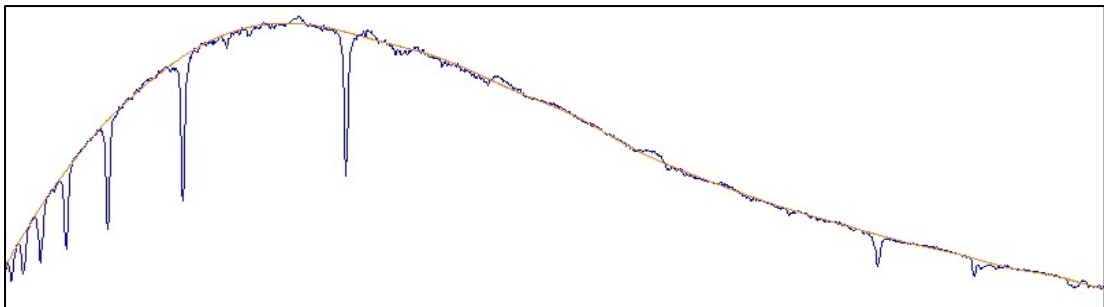

3. If still unknown, determine first the spectral type of the recorded star, e.g. with planetarium programs like Winstars, Redshift, or stellar databases like, SIMBAD [6].

    <u>Note:</u>
    For brighter stars also the Vspec function *(Tools/Spectraltype)* can be applied. This feature requires the enabling of macro execution by Excel defined under *Excel Options/Trust Center*, which however reduces the security level. Alternatively you can directly open the Excel file *brscat2* (Bright Stars Catalog) in the root directory of the Vspec program. For this Vspec function, the required input format is the abbreviated "Bayer Number" e.g. for Rigel *betori* (Beta Orionis), for Betelgeuse *alpori* (Alpha Orionis) or alternatively with the "Flamsteed Number" e.g. *58ori*.

4. Load under *Tools/Library* the synthetic profile of the star model, with a spectral- and luminosity class as close as possible to that of the investigated star. Move the appropriate dat.file from the upper part of the window with click and drag into the profile window. The profile of the star model immediately appears superimposed in the window, named after the spectral type, e.g. 2b9iii.dat (B9III).
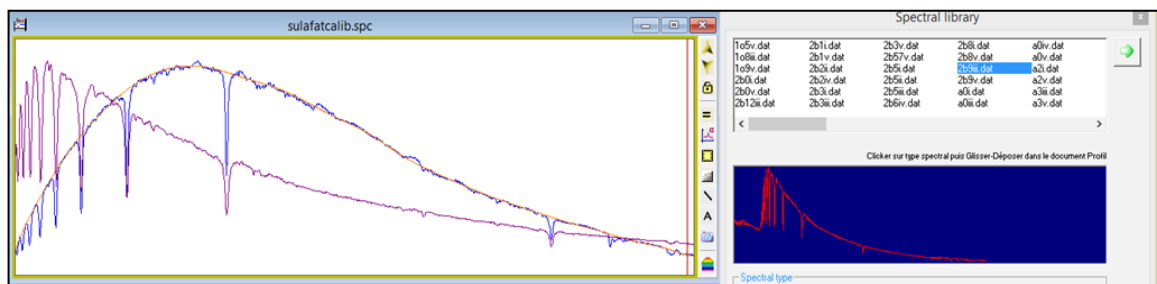
5. Delete all profiles from the window with the icon *"Erase"* .

6. Load the synthetically generated profile of the star model (e.g., 2b9iii.dat) in the window on the left edge.

7. Create continuum fit of the profile, analogously to chap. 7.2, steps 2 − 6. This new profile is titled *"Fit.[Spectral class].dat" (e.g., Fit.2B9iii.dat)*
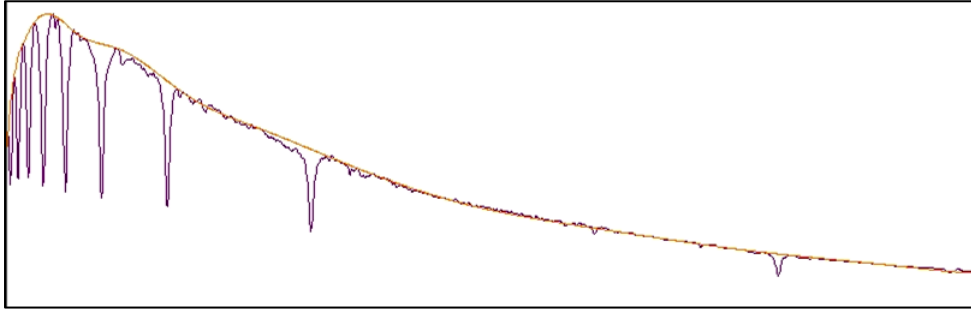
8. Divide *"Fit.Intensity"* by the smoothed model profile *"Fit. [Spectral class] .dat",* as described in chap. 7.2, steps 7 – 11. This correction curve is named *"Division"* and corresponds to the so-called *"Instrumental Response".*
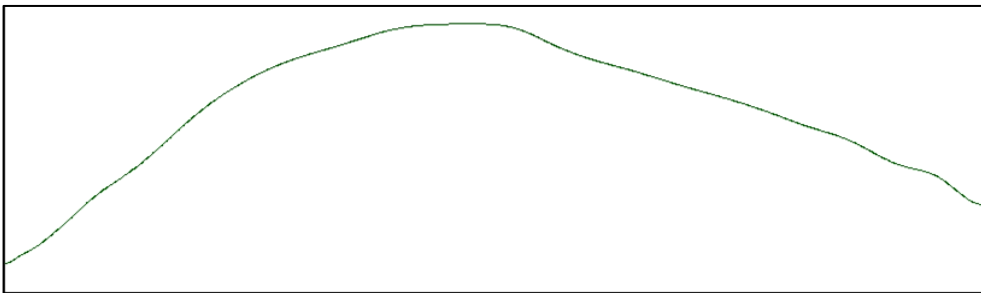
9. By dividing the *"Intensity"* raw profile by the Instrumental Response *"Division"*, the spectral lines of the recorded pseudo-continuum are finally scaled directly to the fitted continuum course of the star model. The procedure runs analogously to chap. 7.2, steps 7 – 11.
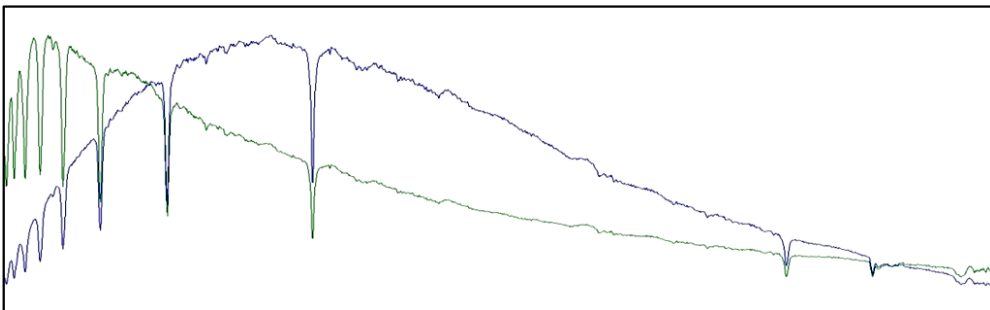
10. Click the „*Replace*" Icon

11. Mark „Intensité"

12. Confirm with OK. As a final result, the radiometrically corrected profile now appears in blue under the name "Intensity" and can now be saved under a different name.
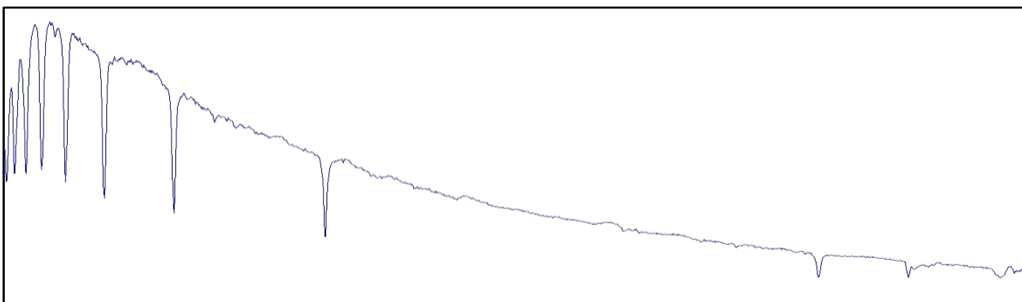
7.6   Relative Flux Calibration by a Standard Star

The principle of this method is described in [1] and works analogously to that in chap. 7.5. The generation of the correction curve "instrumental response", however, takes place here with a separately recorded standard star which must be as close as possible to the examined object. Here it is strongly recommended to first generate and save the response curve in a separate process. Steps 3 − 8 in chap. 7.5 can be skipped and, instead of step 8, this stored response curve is loaded into the diagram. In this section, only the generation of the response curve, generated with the recorded standard star, is demonstrated:

1.   Load the wavelength-calibrated raw profile of the recorded standard star with „*File/Open Profile"* into the Vspec program (if necessary set the file format from *.spc* to *all).*

2.   Generate a fit to the profile of the standard star, analogous to chap. 7.2, steps 2 − 6. This profile is named *Fit.intensity*.

3.   Load the profile of the identical star from the catalog (same HD number), e.g. from the *ISIS_Standardstar Database_v7*. Open the profile with *File/open profile*. The file format must be set under *"filtre"*, depending on the catalog, to *.dat* or *.fit*. The catalog-profile opens in a separate window and must first be copied into the main diagram with Copy Paste. Here it appears superimposed in red and is named *serieX.*

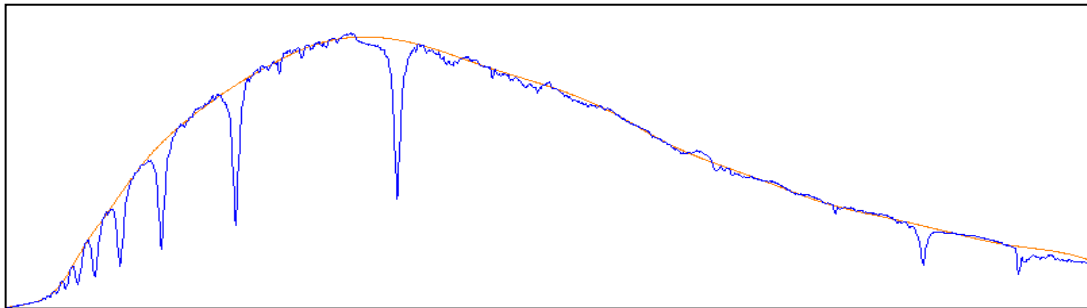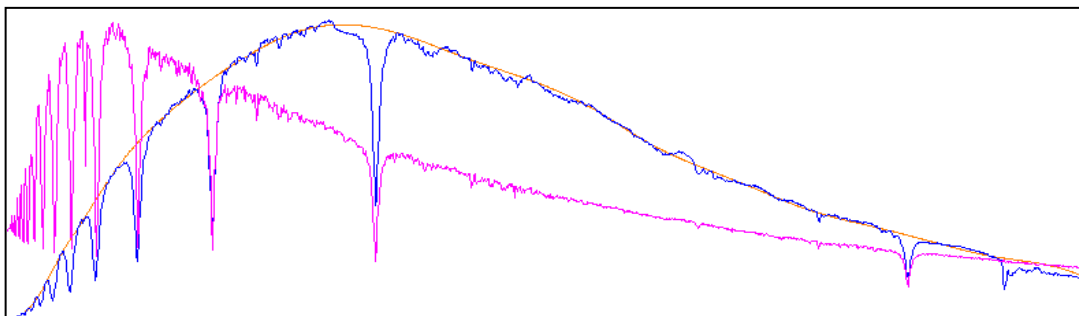4.   Generate a fit to the catalog profile *serieX*, analogously to chap. 7.2, steps 2 − 6. This profile is titled *Fit.serieX*
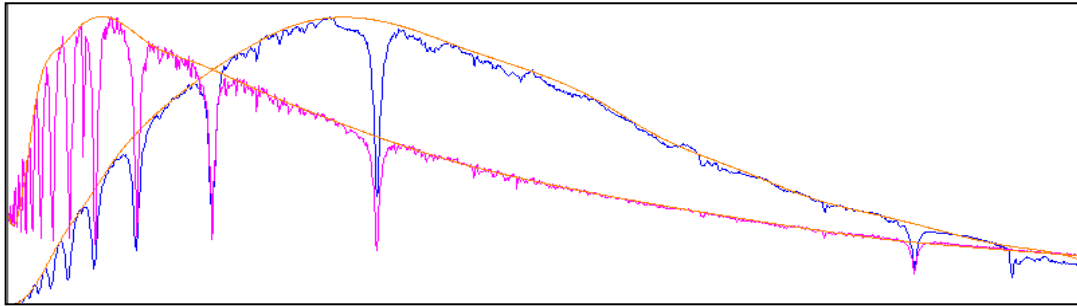
5. Delete all profiles from the window with the icon *"Erase"*

6. Divide the fit of the standard star *"Fit.intensity" by* the smoothed catalog profile *"Fit.serieX"*, analogously to chap. 7.2, steps 7 – 11. This correction curve is named *"Division" and* corresponds to the so-called "Instrumental Response"*. This can now be saved under a new name, e.g. *instrep.*
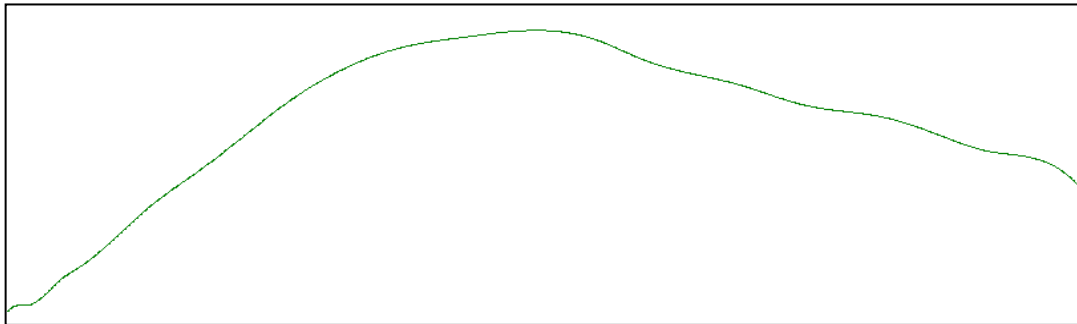
7.7   Search for the Appropriate Standard Star

ISIS [10] contains several catalogs with standard stars. They can be found in the root directory under the folder *isis_database_v7,* most of them stored with the HD numbers in the notation m_HDxxxxxx. To process such profiles they can be loaded in Vspec with *"File/Open Profile"*. Depending on the catalog, the format in the *"filtre"* field must be set to *.dat* or *.fit*. It is worth copying this ISIS Folder with this database into the designated working directory of Vspec.

The HD number of a star increases in principle with increasing right ascension. Therefore, to find a suitable standard star, first determine the approximate range of HD numbering in the vicinity of the examined object. With this information you can search for standard stars with similar coordinates in the various catalogs of the ISIS software. Helpful here would of course be a corresponding list, which is sorted by coordinates!

In the ISIS program, these databases appear under the folder "*5. Profiles"* and the button *"Database"*. With *"Display"* (for example, Miles), the data of the standard stars such as the spectral class, coordinates and profiles can be viewed.

The Miles Library (IAC) is probably the most suitable for broadband spectra. For practical reasons (generation of the continuum fit), the spectral class should be restricted to late B-, A- and possibly early F classes (with the button on the right). It is important that the elevation angles above the horizon are as similar as possible for both objects. This can best be determined with a planetarium program (e.g., Winstars). A table sorted by right ascension can also be found on the Miles homepage. Here, the interstellar reddening E (B −V) can also be viewed for every standard star.

http://www.iac.es/proyecto/miles/pages/stellar-libraries/the-catalogue.php

8 Formatting and Exporting a Spectrum with Vspec

8.1 Formatting the X- and Y-Axis

1. Click on the yellow square on the right edge of the frame. The scaled X- and Y- axes appear.

2. Double-click on diagram area – the pop-up window "Graphic" appears.

   Note: In most cases the default values displayed in "Graphic", generate an un-usable formatting and must be adapted accordingly:

3. *Axis X*:
   Remove the tick in the box *"Auto"* and put e.g. *Nb ticks* on 10 and *tick* on 10. If the labeling appears too dense, the combination 10 and 20 can also be tried. Possibly set the range to be displayed on the X axis with X min and X max. However, this can also be done by marking the desired diagram area with the cursor and cropping with Crop.

4. *Axis Y:*
   Set the desired vertical display range of the curve with *Hi threshold* and *Lo threshold*. If more than one profile is open and you want to apply this customiza-tion to all series, mark *"Apply to all Windows"*. Remove check mark on *"Auto"* and adjust values. If a horizontal profile has been normalized to 1, e.g. set *Nb ticks* to 20 and *tick* to 0.01. For raw profiles, e.g. the combination 5 and 5000 can be tried. The display of the Y axis can also be suppressed by removing the mark in the box *"Y-axis display"*.

8.2 Customize Colors and Fonts

1. Click on the spectral curve *("Intensity")* (or select in the window) and select the curve color with the menu in the header (e.g. *Blue*)

2. Use *Format/background color* poss. to adjust the background color of the dia-gram

3. Under *Format/Line* the line width can be set to 1 or 2 and the font size and type can be adjusted with *Format/Font*.

8.3 Presentation of Several Superimposed Curves

To compare the intensity of multiple profiles – even with non-rectified profiles – they can be displayed superimposed in one single diagram:

1. Previously normalize all profiles, to be overlaid according to chap. 7.3, to the same continuum section to unity (Ic = 1).

2. To display superimposed, copy these normalized spectra with *copy/paste* into one diagram.
   Note: Under *Options/Preferences/Continuum* you can enter the start- and end wavelength to ensure an uniform reference section.

3. In the box *"Axis Y"*, the position with respect to the Y-axis and the desired ampli-tude of the selected curve can be set with *"Hi threshold"* and *"Lo threshold"*. The curve to be formatted can be selected by mouse click or in the window on the left edge of the header. If the amplitudes have to be adjusted, this must be done proportionally equal for all curves, to grant a valid intensity comparison.

8.4   Export the Formatted Graphic

With *file/export*, a screenshot of the current display on the screen can now be created in various formats (for example, jpg, bmp).

Note: In the Vspec program, *"save as"* only saves the calibration and normalization. The graphic formatting, but also the superposition of several profiles, are getting lost!

8.5   Create a Synthetic Spectral Image

Derived from the intensity profile, a synthetically generated, colored spectral image can be generated. This may e.g. just be used for later commenting of the spectrum or as a graphical complement to the spectral profile. The brightness and contrast of this synthetic spectral image is sensitive to the formatting and position of the profile with respect to the Y-axis. Therefore, often a further editing in Photoshop is necessary.

1.   Select *Tools/Synthesis* (spectral strip appears in black and white)
2.   Color display: right click on the spectral strip and click *"colorer"*
3.   Export under the desired file format and name with *"exporter"*.

Note: In Photoshop, the image can be further edited.

8.6   Assembly of Overlapping Spectral Profiles

Preliminary remark: With this method, two calibrated spectral profiles can be assembled, which slightly overlap at the interface. This function is best performed on profiles with a rectified continuum (chap. 7.2). A practical example is displayed in chap. 14 by assembling of two echelle orders.

1.   Open the two calibrated profiles (.spc) in Vspec.
2.   If not already done, rectify both profiles by removing the continuum course according to chap. 7.2.
3.   Under *"Operations"* select the command *"Join"*. The window *"Selection"* appears with a File Explorer and a blue display
4.   Double-click on the both folders so that the "intensity" files are displayed.
5.   Click both boxes with *„intensity"* files. The according profiles are displayed in the blue window.
6.   Confirm with *Ok*. A new window with the composite profile (green) appears under the name *"NewSpc-0"* and can thus be saved.
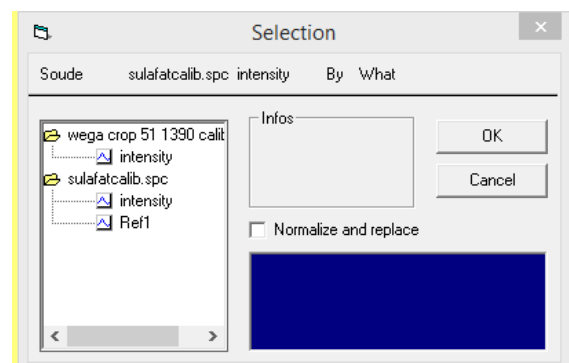
   This procedure is relatively delicate. If the message appears *"The two series do not superpose"*, the composition can be retried by cropping a modified overlap area.

9   Quantitative Information in the Spectral Profile

9.1   Preliminary Remark:

Here the practical extraction of quantitative information from the calibrated and normalized spectral profile is described. Theoretical basics see [1].

9.2   Info Based on Marked Single Lines or Profile Sections

1. Mark the desired line by *click and drag*

2. Right-click to call Popup Menu. Alternatively, it can also be called up by *Spectrometry/Computation Preferences*.

3. Click *Computation*

4. Tick the desired values in the popup field

5. Confirm with *OK*

6. The results are displayed in the blue display window (delete with reset):

   <u>*SNR:*</u> Signal Noise Ratio in the spectral profile - the bigger the better. This value is not determined at a single line but within a larger, marked section. The choice of a reasonable reference area is tricky.

   <u>*FWHM:*</u> Full Width at Half Maximum Height of a spectral line [Å]

   <u>*EW:*</u> Equivalent Width of a spectral line [Å]

   <u>*Barycenter:*</u> Centroid of the line profile [Pixel]

   <u>*Line Center:*</u> Wavelength of the spectral line i.e. of the barycenter [Å]

   <u>*Area:*</u> Area of the line profile

   <u>*Std deviation:*</u> Standard deviation of the curve in the area of the line profile

   <u>Notes</u>

- FWHM and EW (LEQ) should, with few exceptions, always be measured by a Gauss fit of the original profile, as is common in the professional field today. This curve is generated by *Spectrometry/Gaussian Fit*. In this case FWHM is calculated and displayed directly. However, EW (LEQ) must be determined at the Gaussfit according to the above displayed steps 1 – 6 with several, possibly averaged measurements, since the result reacts sensitively to the marked area.

- The selection of the marked area can also be done more reproducibly with an autoselect function under *Options/Preferences/References*. First enter in the box *"Auto Selection line width"* the estimated width of the entire spectral line in [Å]. With pressed *ctrl* key then just click the line and the selection takes place automatically.

- The EW value can only be determined after a normalization of the profile to unity (Section 7.3). Thereby the selected section for normalization has no noticeable influence on the result!

9.3   The Determination of Spectral Sampling

In the upper menu bar , as a measure for the dispersion, the "Spectral Sampling" of the profile, obtained with the specific pixel grid of the applied camera, can be read in [Å/pixel].

9.4   The Determination of the Photosphere Temperature

The inclination of the continuum $dI/d\lambda$ allows the estimation of the photosphere tempera-ture, in Vspec called „*Temperature de Planck*".The principle is described in [1] and in the Vspec Manual [11]. This requires a relative flux calibration of the profile with standard star according chap. 7.6. Based on the slope of this profile, finally, the *"Température de Planck"* can be read:

1. Select *Radiometry/Planck*

2. Enter the estimated photosphere temperature of the star in the pop-up temperature window

3. Change the value iteratively until the displayed curve (for example P_3200) runs as parallel as possible to the radiometrically corrected continuum.

10 The Line Identification

The principle and the strategies of the line identification are described in [1]. Here follow some hints for according tools in Vspec. Under *Tools/Elements* you will find element and ion lists for several object classes (3000 − 10'000 Å). The prerequisite for the analysis is a high-resolution spectrum which is calibrated according to rest wavelengths and thus is neither red nor blue shifted. Clicking on a specific position on the loaded profile immediately marks in the list the entry with the nearest wavelength. The box *Elements* allows for ions or elements to be specifically selected and transferred to the calibrated profile for display by *Sort* and *Export*.

lineident

This list is used for identifying unknown elements or ions in stellar spectra.

element

This list has proven to be useful when evaluating laboratory spectra, e.g. for determining the gas composition in a discharge lamp or calibration light source.

sun

Contains solar absorptions between 6000 und 6800 Å

nebplan

Contains emission lines typical appearing in emission nebulae

atmos

Contains the atmospheric H_2O lines around the Hα line.

11 Scaling the X-axis in Doppler Velocity

For the display e.g. of star rotations and velocity variations in binary star systems, it makes sense to scale the wavelength axis in the range of the investigated line profile, instead of the wavelength [Å], converted into Doppler velocity [km/s].

1. Open in Vspec the profile, wavelength calibrated, rectified and normalized to unity, with „*file/open profile*" (if necessary set the file format from *.spc* to *all).*

2. Click on the yellow square ▨ on the right edge of the frame. The scaled X- and Y-axes appear.

3. Mark with *Click and drag* the desired zoom range around the line to be measured and activate it with the magnifying glass icon 🔍.

4. Double-click on the diagram area – to activate the pop-up window "Graphic" .

5. Deactivate *"Auto"* in the "Axis Y" section and, for example, set *Nb ticks* to 50 and *tick* to 0.002 to achieve a reasonable scaling of the Y axis.

6. Restrict the displayed area of the Y-axis in such a way that the intensity curve of the line fills a large part of the diagram height. In the *"Axis Y"* section, adjust the *"Hi threshold"* and *"Low threshold"* values accordingly and confirm with *Apply*.

7. Move the part of the curve to be examined by the section *"Axis X"* with appropriate values for x_{min} and x_{max} to the left near the intensity axis.
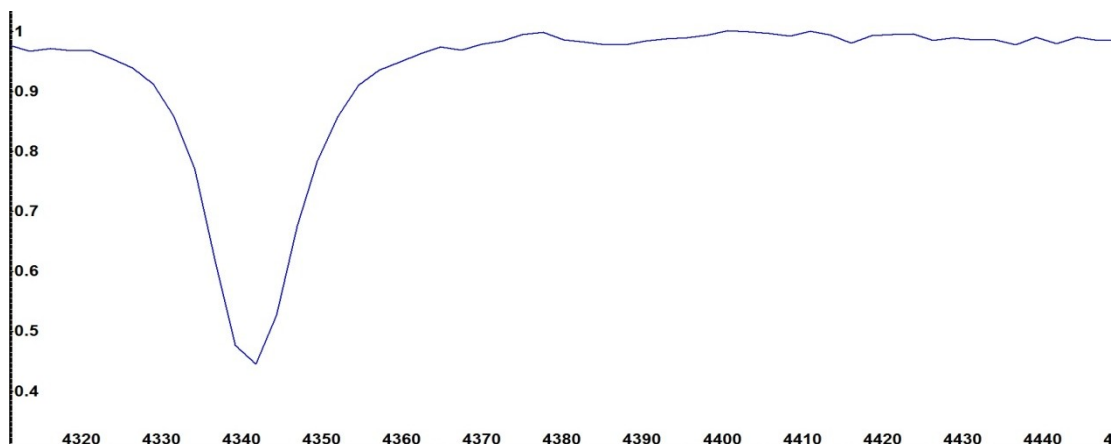

8. Adjust the font under *Format/Font*

9. In the section *"Axis X"*, mark the Doppler box. Disable the *"Auto"* box and set *Nb ticks* to 10 and *tick* to 1 typically. Furthermore, the central wavelength λ_{r0} of the line must be entered in the *"lambda"* field.
   Notes:
   This value will now define the 0 point on the wavelength axis from which the Doppler velocities are plotted in the red direction (positive values) and in the blue direction (negative values). In many cases, λ_{r0} corresponds to the measured wavelength of the profile. Often, however, also Doppler shifts are displayed this way (for example in the case of spectroscopic binaries). This then requires a corresponding adaptation of λ_{r0}. If the box *1000km/s* is marked, Vspec automatically scales the displayed area of the X axis from -1000 km/s to +1000 km/s.

10. Confirm with *Apply*

11. The X-axis appears now scaled in Doppler speed
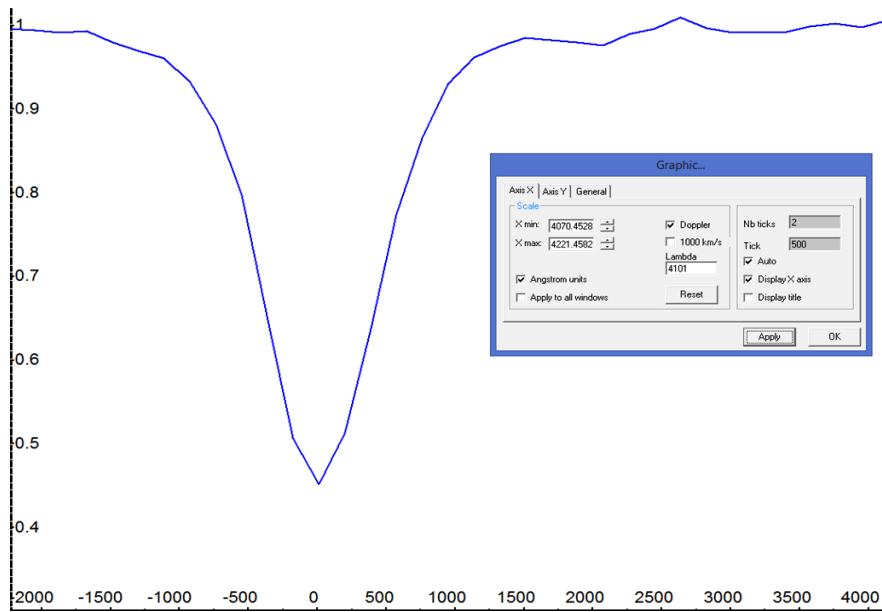
12. In some cases the correct display of the scale may still require an adjustment of the tick values in the section *"Axis X"*. If the zero point should now be wrongly labeled e.g. with −2 km/s instead of 0 km/s, the *Nb Tick* value is usually too low. Sometimes changing the zoom range will also help.

13. The resulting diagram can now be saved with *"File/Export bmp"*.

12 Heliocentric Corrections

12.1 Heliocentric Correction of the Radial Velocity

Here, a topocentrically measured radial velocity $v_{r_{measured}}$ evaluated by Vspec is reduced to the generally applied heliocentric viewpoint $v_{r_{Hel}}$. For this purpose, the average orbital velocity of the earth around the sun (about 30 km / s) and further the influence of the earth's rotation on the measured radial velocity of an object, must be compensated:

1. Under *"Preferences/Position"* enter the coordinates, altitude and time zone of the observation site (Western longitude and southern latitude negative −).

2. In the Vspec program activate *"Spectrometry/Heliocentric correction"*. Under *"Site coordinates"* you can see the location coordinates of the observation site, entered in step 1.
    Note This function can only be activated if any profile is loaded!

3. Under *"Object coordinates"* in the line *"Alpha"*, enter the right ascension and in the line *"Delta"* the declination of the observation object with the correct sign.

4. Under *"Date"* the date is entered, whereby the observation time is expressed as a decimal value, proportional to the day length of 24h. 3.75 means e.g. the 3rd day of the month, 18'00.

5. By default, the λ_0 value of the Hα line appears under *"Lambda ref"*.

6. The calculation is triggered by clicking on "Compute".
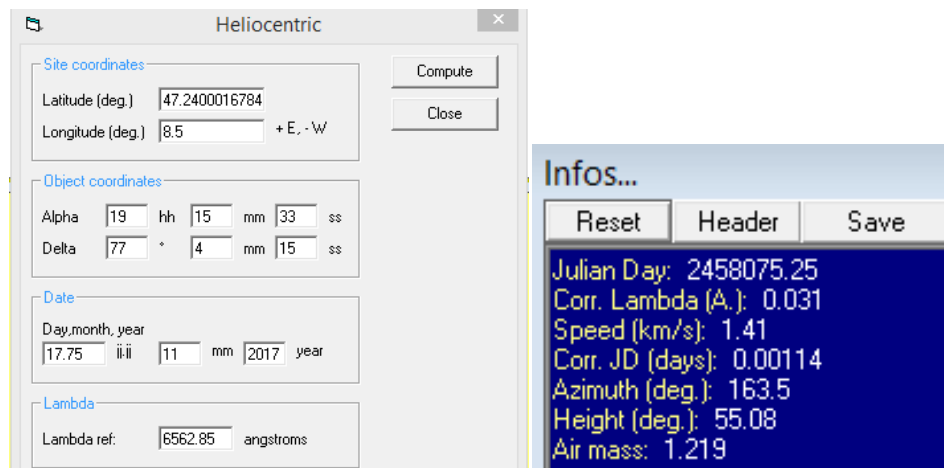
12.2 Evaluation of the Calculated Data

Julian Day: Julian date of the entered observation date/time

Corr. Lambda: Amount in [Å] by which a recorded profile appears displaced due to heliocentric earth movement

Speed: Heliocentric correction speed $v_{r_{korr}}$ in [km / s] by which the measured radial velocity of the object $v_{r_{measured}}$ must be corrected.

$$v_{r_{Hel}} = v_{r_{gemessen}} + v_{r_{korr}}$$

Corr. JD: Correction value [days] to heliocentrically correct the time of an observed event. Example: *0.00114* x 24 x 60 = +1.64 minutes

Additionally indicated are here azimuth and elevation, as well as the "Airmass", i.e. the light path of the object through the Earth's atmosphere, relative to the minimum distance in the direction of the zenith.

Notes:

- The signs of the determined values must be algebraically correctly applied in the formula.

- The calculated $v_{r_{Hel}}$ can be checked for Milky Way objects in CDS SIMBAD [6] and for extragalactic objects in the NED (NASA Extragalactic Database) [7].

- Comparing measurements of many objects with known radial velocities (e.g., sun) allows for the detection of any systematic bias that may be corrected in future measurements.

12.3 Correction of the Doppler Shift in the Spectral Profile

After performing steps 1 – 6 in chap. 12.1, the wavelength calibration of the loaded profile by the value Corr. Lambda can be corrected to the rest wavelength λ_0.

1. Start the correction process with *Spectrometry/Heliocentric* speed correction.
   In the pop-up field, the heliocentric correction velocity appears $v_{r_{korr}}$. appears as the deviation to the rest wavelength λ_0. This number can also be overwritten with another value.

2. *Start the adaption of the calibration of the loaded profile by clicking „Appliquer".*

3. The adjusted "Intensity" profile can be saved under a new name

Note: If the profile contains known spectral lines, it can of course also be recalibrated to rest wavelengths λ_0.

13 Intensity Distribution of Ions within an Emission Nebula

Spectrographs with a long slit allow 2D- appearing objects such as emission nebulae, to map the intensity profile of a given spectral line along the entire length of the slit. This allows rough conclusions about the distribution of the emission strength the corresponding ion produces at a specific wavelength.

This example from the spectral atlas [2] shows the planetary nebula M57, supplemented with a drawn 50µm slit. At 2000mm focal length, the slit length exceeds ideally just barely the diameter of the nebula projected in the slit plane. Here, the different intensity courses of the two strongest appearing emission lines, O III at 5007Å and N II at 6584Å, have been evaluated.

Since DADOS aligns all three slits in a line, this array can be evaluated as a "long slit" with two short gaps. The different slit widths hardly play a role here, since only the intensity profile is evaluated. As an example, see the cross sections through M42 in the Spectral Atlas [2].

Prerequisite for this procedure is an accurate tracking, possibly even supplemented with autoguiding, which ensures that the slit position with respect to the object shows no significant shift. In order that a serious, subsequent analysis is possible, the exact slit position with respect to the nebula must be documented, e.g. by a screenshot.

Intensity Profile [O III] λ 5007

Intensity Profile [N II] λ 6584
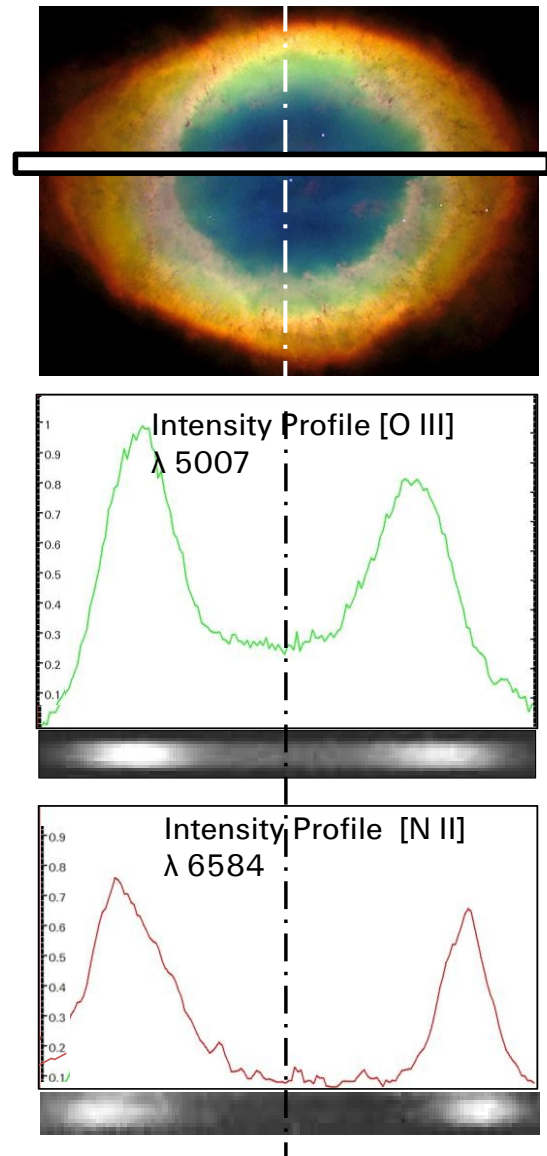
Note:

IRIS and Vspec have no designated function to accomplish this special task. However in the following it will be shown, how such an intensity profile can be generated, applying these programs combined with some "artifices".

1. Load in IRIS with „*file/load*" an image processed according chap. 3.4


2. Rotate the image by 90 ° with *Geometry/Rotate* according to chap. 14.1. The individual spectral lines should now run horizontally, otherwise adjust the angle of rotation. This and the following steps are only demonstrated on the O III line.
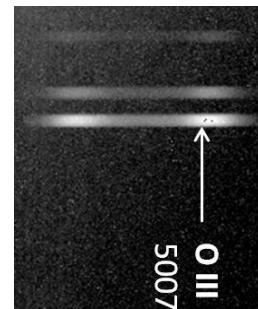
3. Generate a 1D intensity course along the slit length:
   Frame the line with the cursor and apply *Spectro/2D -> 1D optimal addition* (according chap. 3.2, steps 7 − 8).

4. Save the 1D intensity course for further processing with Vspec

5. Load the 1D intensity course in Vspec and generate an intensity profile according chap. 4.2, steps 1 − 3.
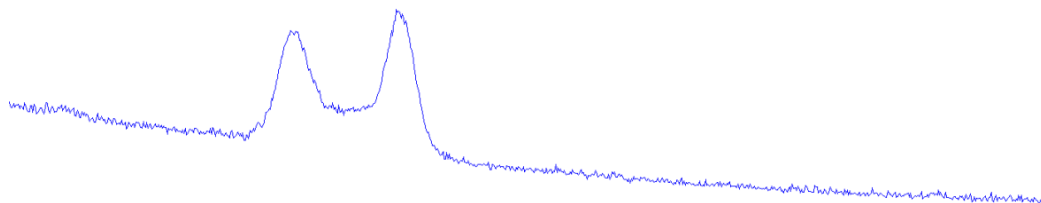
Note: With Vspec, the continuum can *only* be rectified at a wavelength-calibrated profile, why a *purely fictitious* and *arbitrary "pseudo-calibration"* must be performed here. Following the easiest way:

6. Select *Spectrometry/basic calibration*

   e.g. input for
   Line 1: 6563 to Pixel No. 340 and
   Line 2: 7600 to Pixel No. 1200

7. After confirming with OK the profile appears with the arbitrary pseudo-calibration, just to enable the further steps.

8. Rectify the course of the continuum analogously to chap. 7.2, steps 1 − 15. Exception: Only points on the left and right side of the intensity profile should be marked.
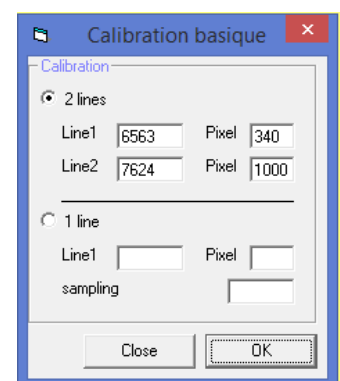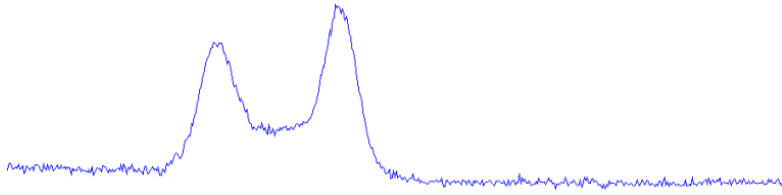
9. Crop the profile to the area of the intensity profile and export it as Bmp or Jpeg. When formatting the intensity scale, it may make sense to select the highest point as 1 and the base of the profile as 0 (see graphic above from M57).


10. The graphic may now be imported e.g. into PowerPoint for further formatting and labeling.

14 The Processing of Echelle Spectra

14.1 The Evaluation of Individual Orders

In most cases Echelle spectra are obtained for the high-resolution investigation of specific lines. Here, the much simpler evaluation of individual orders is often sufficient. However, the prerequisite is that they are only slightly curved and the spectral lines are reasonably perpendicular to the wavelength axis. Therefore, also profiles, generated by Baches- and SQUES spectrographs, can be conventionally processed, calibrated and formatted as with ordinary grating spectrographs.

Due to a mostly present, if only slight curvature of the strip, it's leveling requires some care. This adjustment should be performed *before* the recording by the mounting angle of the camera and recording the daylight or calibration light source. It is the aim to strive for a reasonable compromise through trial and error. By software, the rotation of a spectral image in IRIS can be done via "Geometry / Rotate":
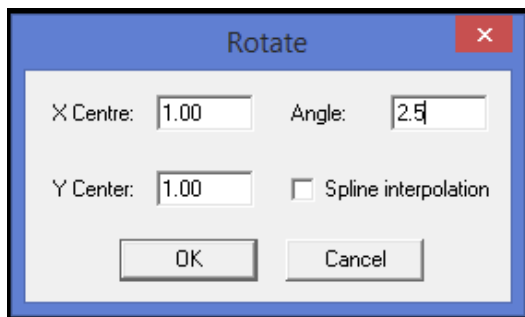

The X- and Y- values define here the pixel coordinates about which the rotation (angle) of the strip is to take place. Of course, this procedure must be repeated identically for the calibration spectrum.

14.2 Overview of the Processing Steps

The following graphic first provides a rough overview of the individual steps of data reduction. Order 43 from the Arcturus spectrum contains the striking magnesium triplet (Fraunhofer b) in the range of approximately 5160 – 5190 Å. This area should be shown here as a section.

Horizontally leveled raw recording of order 43, Arcturus α Boo
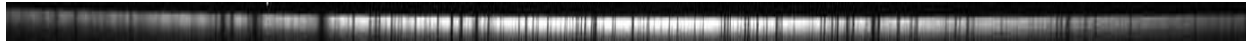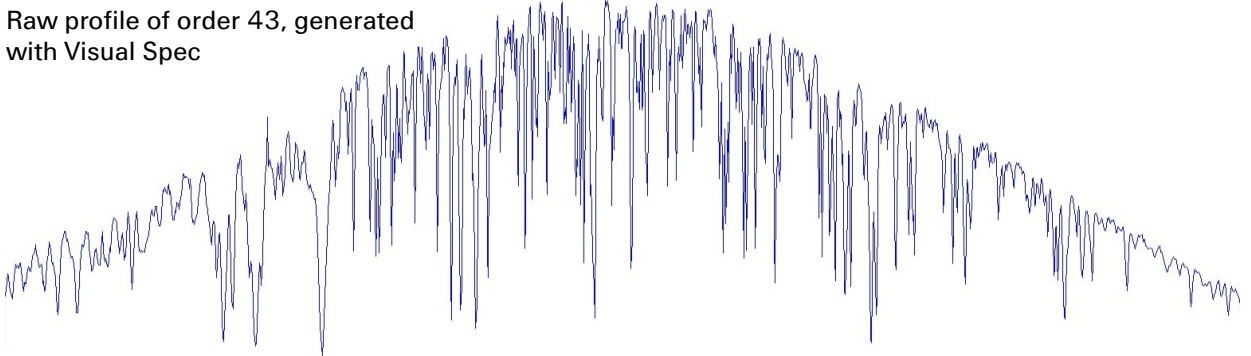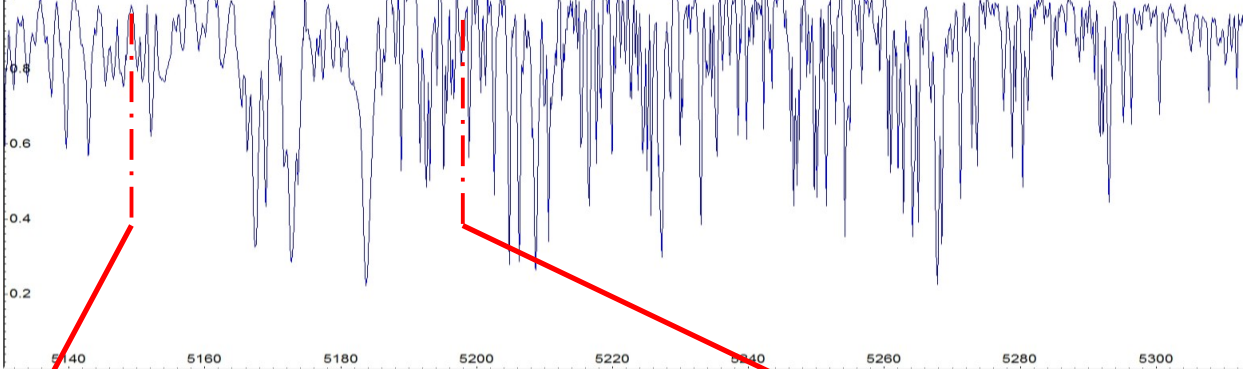
1D Spectrum of order 43 after processing with IRIS

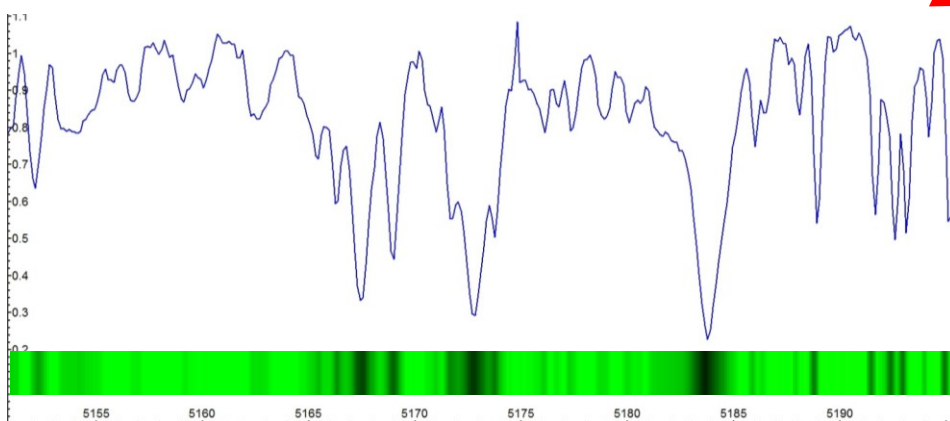1D RELCO calibration spectrum of order 43 after processing with IRIS

Raw profile of order 43, generated
with Visual Spec

Spectral profile of Arcturus, Order 43, calibrated rectified, and normalised to unity Ic = 1 with
Visual Spec

Cut out of the Magnesium Triplet Arcturus, Order 43 with Visual Spec

14.3 Detailed Presentation of the Process

The entire process is demonstrated here using the example of the impressive and finely structured Fraunhofer A line. The following section of a SQUES-Echelle spectrum of the daylight shows this absorption, distributed among orders 29 (top) and 30 (bottom).

Because this broad spectral feature extends over two orders, both must be evaluated separately and then, according to chap. 8.6, be assembled.
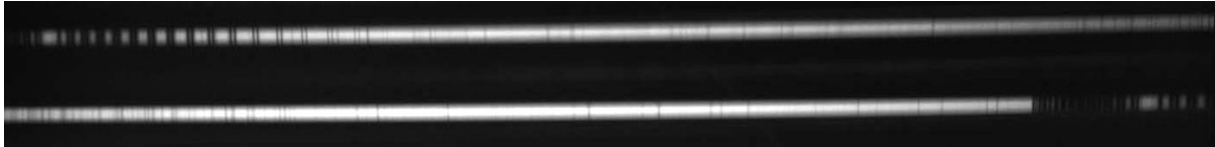
1. The data reduction takes place, with one exception, according to steps 1 – 9 in chap. 3.2.   Step 5 is omitted here, because with Echelle spectra, due to low slit height, the sky background can only be subtracted as a separate recording.

2. After step 9, the processed orders 29 and 30 are displayed here as 1D strips. They are shown slightly widened.


3. The calibration spectrum must be processed analogously to the object spectrum (not shown here).

4. Generate the raw profiles for the orders 29 and 30 according to chap. 4.2.
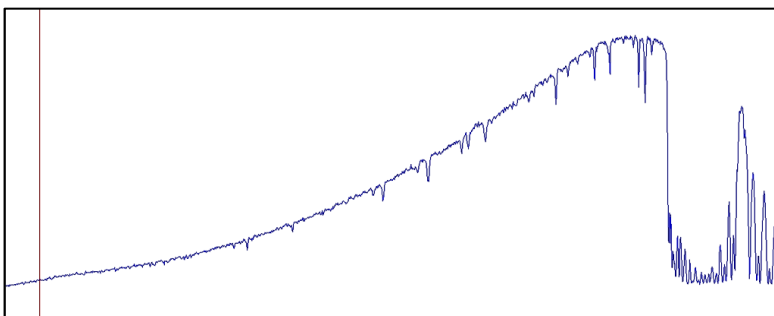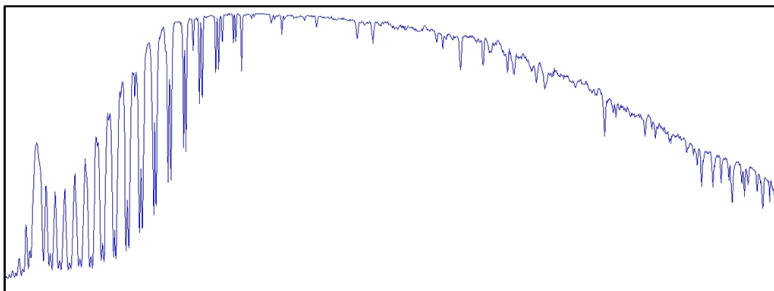

5. Now both orders have to be *not linearly* calibrated with the corresponding calibration spectra according to chap. 5.3, or calibrated on the basis of known lines (chap. 5.2). These steps are not demonstrated here.

6. In these calibrated profiles, the area of the Fraunhofer A line is now marked with the cursor and cropped with the icon .
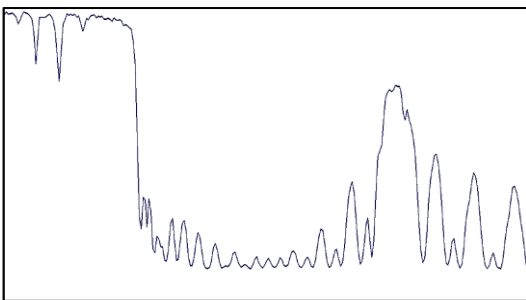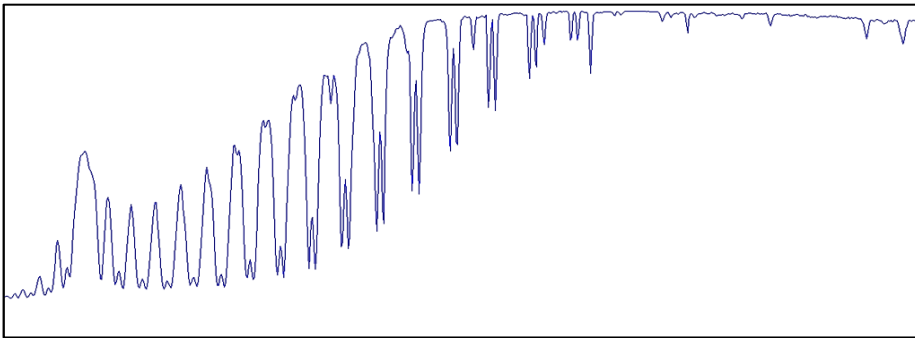
7. Rectify the continuum course according chap. 7.2 (here poss. already after step 5)
8. Finally assemble both profiles in Vspec with *Operations/Join* according to chap. 7.6.
9. Further editing and formatting as with a normal spectral profile

Here is the final result after rectifying the continuum course according to chap. 7.2.
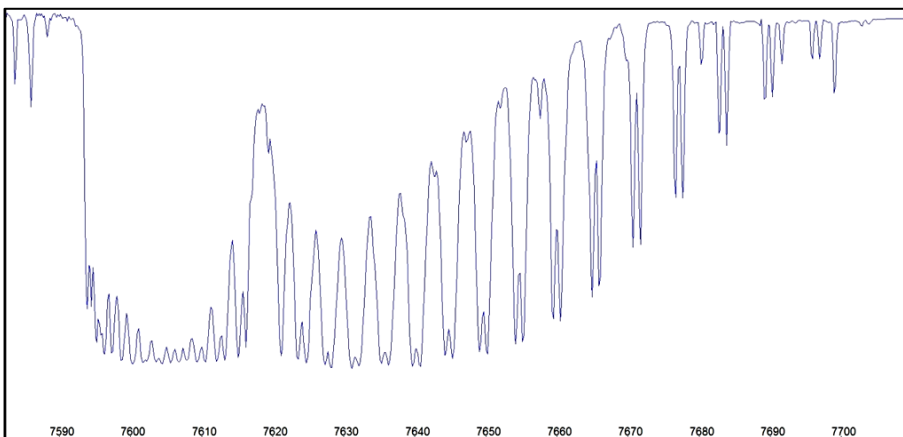
15 Bibliography and Internet

Literature:

[1] Marc Trypsteen, Richard Walker: *Spectroscopy for Amateur Astronomers - Recording, Processing, Analysis and Interpretation,* ISBN: 9781107166189

[2] Richard Walker: *Spectral Atlas for Amateur Astronomers - A Guide to the Spectra of Astronomical Objects and Terrestrial Light Sources*, ISBN: 9781107165908

Internet Links:

Author:

Various publications on the topic spectroscopy can be downloaded at this link:

[3] http://www.ursusmajor.ch/astrospektroskopie/richard-walkers-page/index.html

[4] *Glow Starter RELCO SC480 Atlas of Emission Lines – Recorded by the Spectrographs SQUES Echelle and DADOS*
http://www.ursusmajor.ch/downloads/sques-relco-sc480-calibration-lines-5.0.pdf

Tutorials:

[5] DADOS Tutorial by Bernd Koch
http://www.baader-planetarium.de/dados/download/tutorial-dados-d.pdf

Databases

[6] CDS Strassbourg: *SIMBAD Astonomical Database* with the most important data about astro objects like stars, galaxies, star clusters etc. http://simbad.u-strasbg.fr/simbad/

[7] *NASA Extragalactic Database (NED)* with the most important data, spectra, images etc. on galaxies and quasars http://nedwww.ipac.caltech.edu/

[8] *The SAO/NASA Astrophysics Data System*, Database of astrophysical publications
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http://physics.nist.gov/PhysRefData/ASD/lines_form.html

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[10] IRIS and ISIS: Webpage of Christian Buil
http://www.astrosurf.com/buil/

[11] Vspec: Webpage of Valerie Désnoux
http://astrosurf.com/vdesnoux/

[12] RSpec: Webpage of Tom Field
http://www.rspec-astro.com/

[13] *SpectroTools:* Freeware programm by Peter Schlatter for extraction of H_2O lines
http://www.peterschlatter.ch/SpectroTools/

[14] *MIDAS*, ESO
http://www.eso.org/sci/software/esomidas//

[15] IRAF, NOAO, http://iraf.noao.edu

[16] *SimSpec V4, Spectrograph Exposure Time Calculators (ETC)*: Excel based program
http://www.astrosurf.com/buil/us/compute/compute.htm

[17] BASS, Basic Astronomical Spectroscopy Software, Restricted Yahoo Group
https://uk.groups.yahoo.com/neo/groups/astrobodger/info