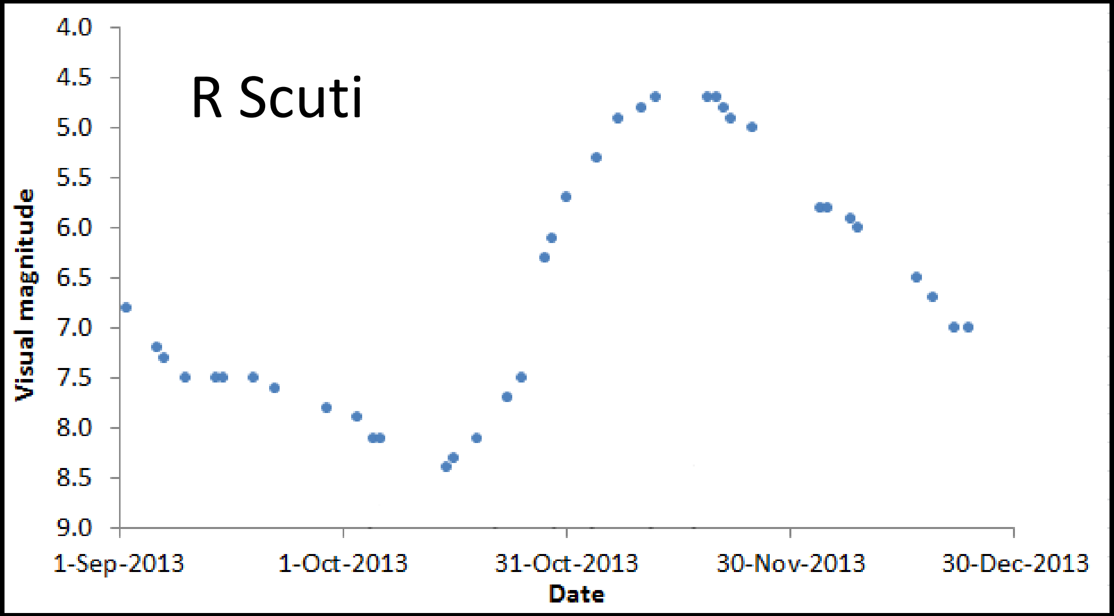
Scientific analysis of amateur spectra

David Boyd
BAA, ARAS, AAVSO

Workshop delivered at the Society for Astronomical Sciences Symposium, Ontario, California, May 2019

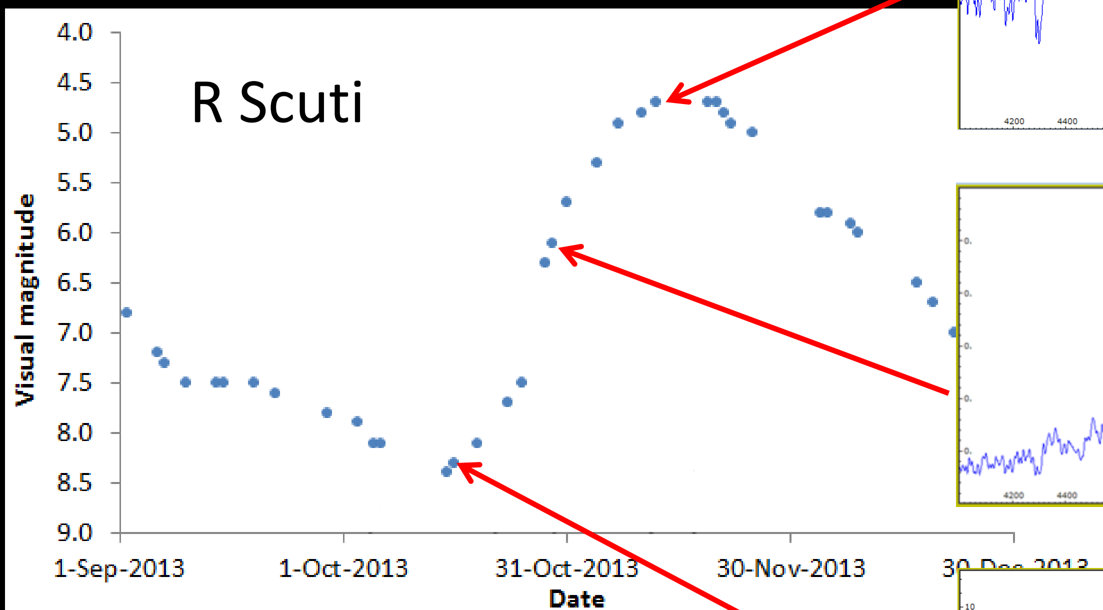
Why do spectroscopy?

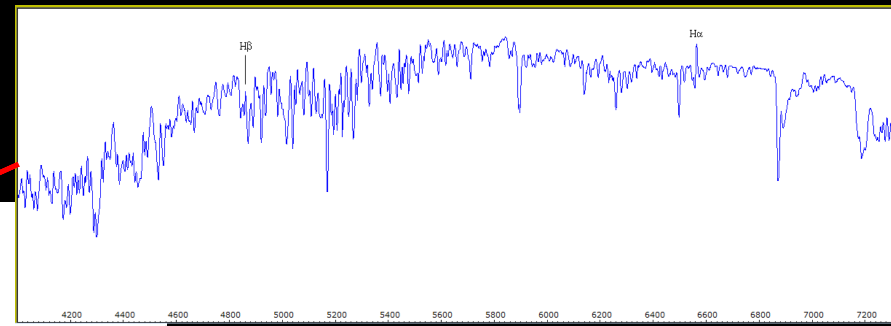
Photometry shows changes
in a star's brightness.

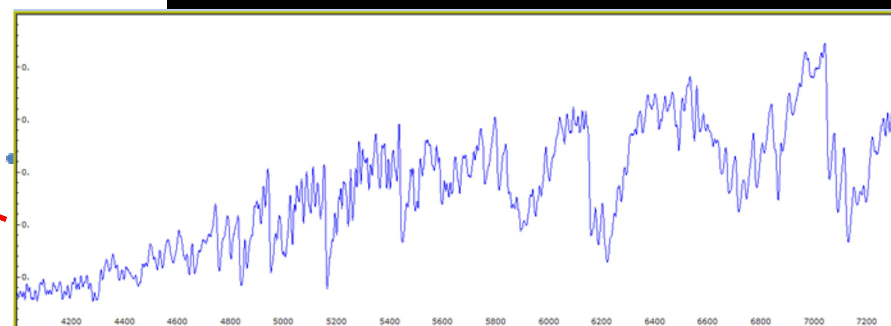


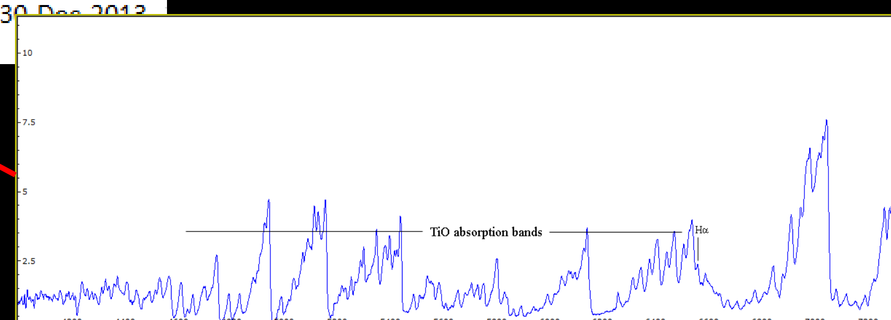
Why do spectroscopy?

Photometry shows changes in a star's brightness.









Spectroscopy reveals what is happening as the star brightens.

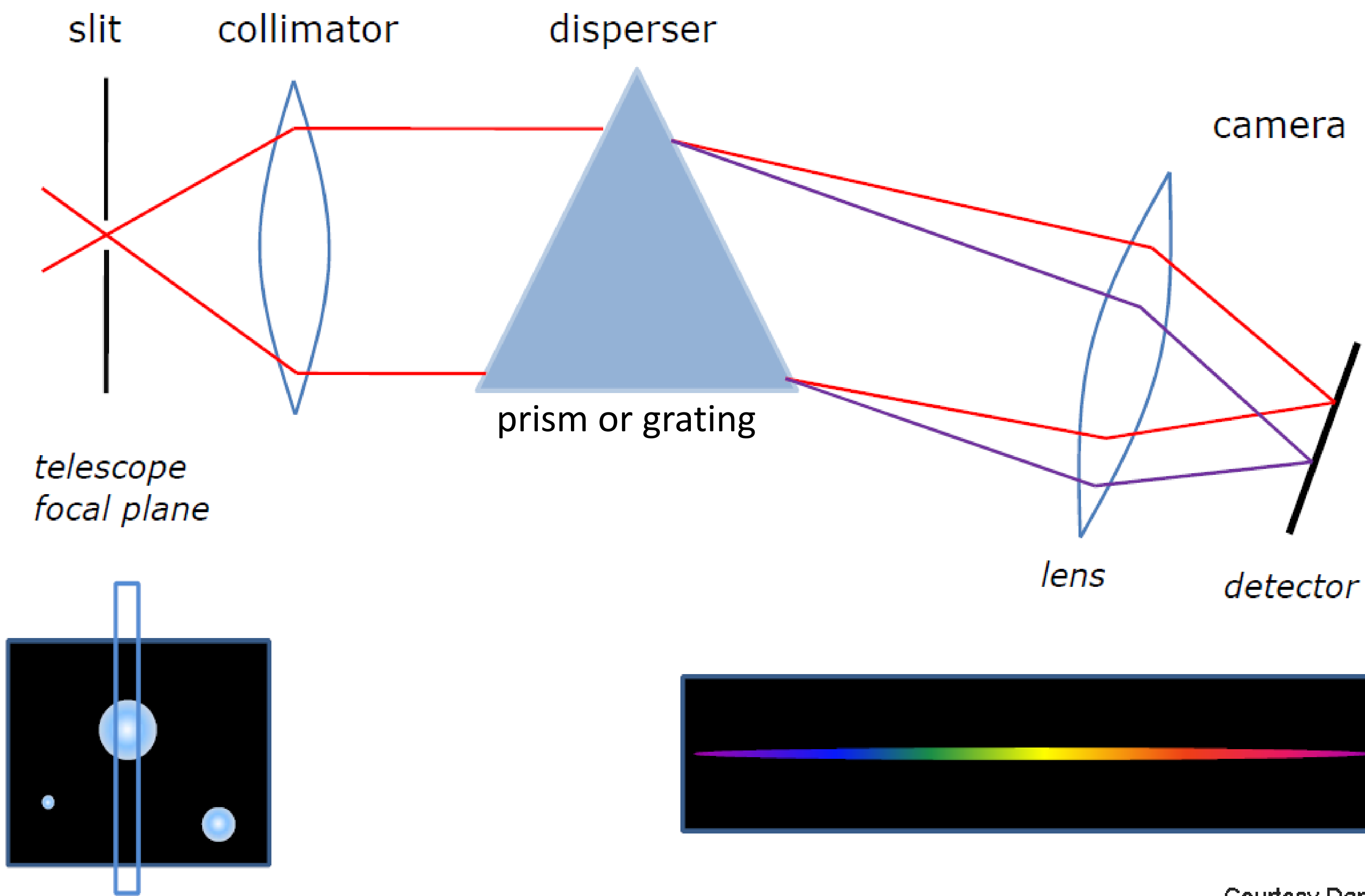
Star Analyser SA100

SA100 is a transmission diffraction grating manufactured by Paton Hawksley.

- 100 lines/mm
- mounted in a normal 1¼" filter holder
- designed to be mounted in front of a camera or behind a telescope
- very low resolution
- relatively inexpensive
- simple introduction to spectroscopy

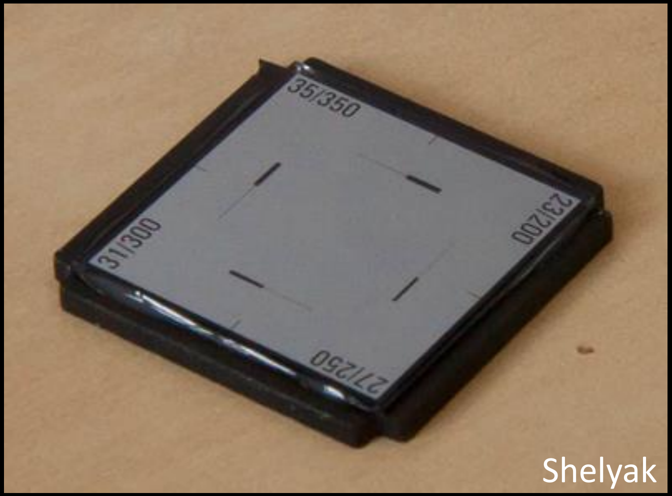
Photo courtesy of Robin Leadbeater

The basic slit spectrograph



Courtesy Danny Steeghs

The slit



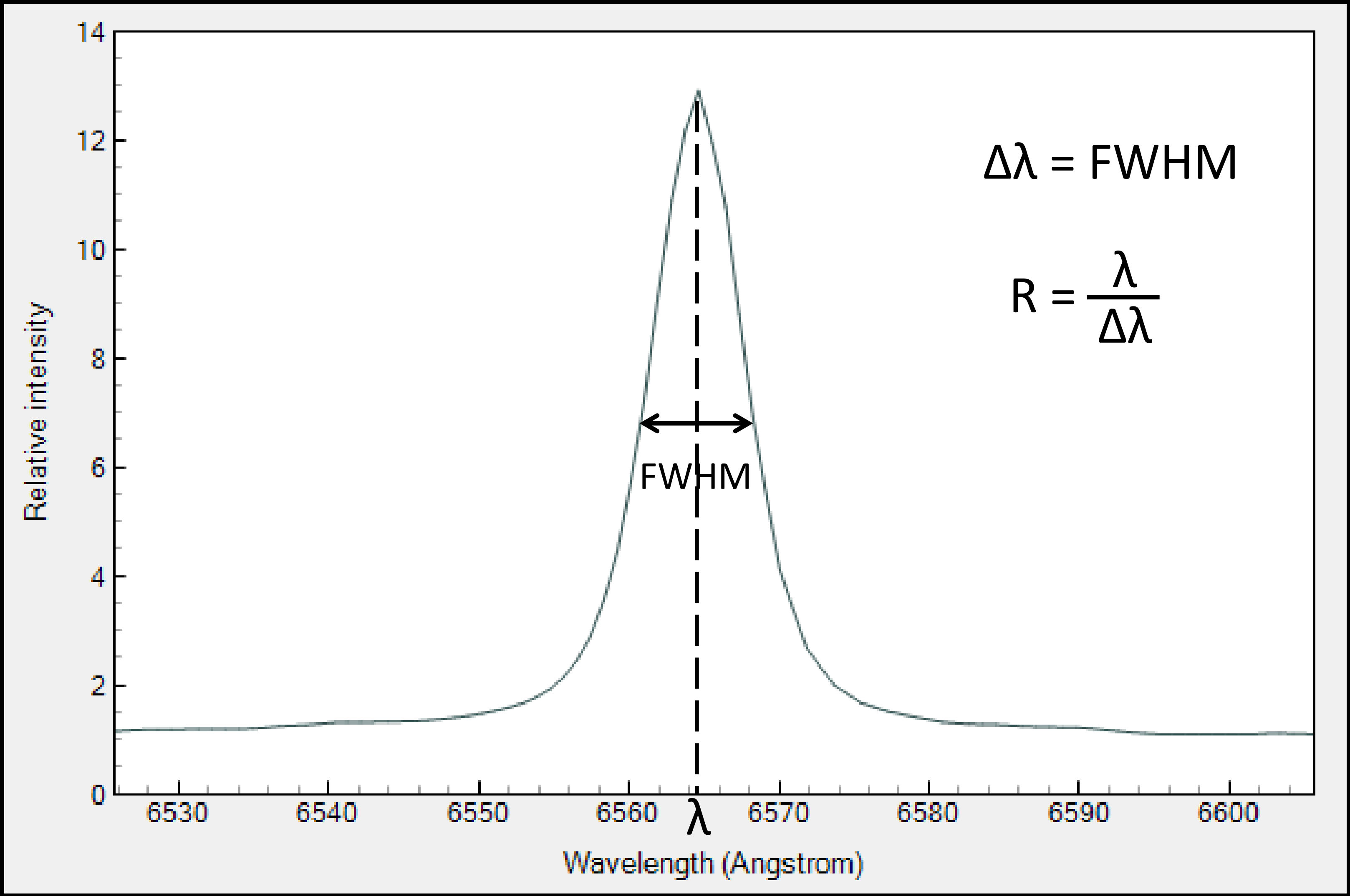
Reduces background so improves SNR.

Slit width defines the FWHM of spectral lines and hence the spectral resolution R.

Typically matched to the seeing resolution of the observing site, in my case around 3 arcsec -> 23 µm slit in a LISA spectroscope on a C-11 scope at F/5.

Trade-off between wanting all light from the star to pass through and achieving as high resolution as possible.

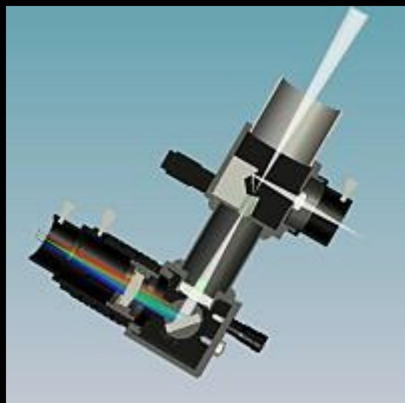
What is spectral resolution = R ?



FWHM = 6 Å λ = 6563 Å   R = 6563/6 = ~1000

Some commercial amateur spectrographs

$R = \lambda/\Delta\lambda$



DADOS R ~500

ALPY R ~600

SX R ~2000

LHIRES R ~17000

LISA R ~1000

ECHELLE R ~10000

DIY spectroscopy

Amateurs are now starting to develop their own spectrographs using 3D printing.

This is Tony Rodda's implementation of the LowSpec2 design published by Paul Gerlach.

Compromises!

As in most things, spectroscopy involves making compromises.

An important one is between the spectral resolution and wavelength range you want to work with.

This depends on the sort of science you want to do, e.g.

a) do you want to observe the whole optical spectrum of a star, perhaps to follow its changing temperature as it pulsates, or
b) do you want to study changes in, say, the Hα emission line of a Be star in great detail?

Each optical design of spectroscope has a wavelength range over which it will produce good quality spectral lines.

Resolution vs wavelength range

Low resolution (R < ~2000) lets you observe the whole optical spectrum.

- e.g. Shelyak ALPY and LISA range is from 3800 to 7400 Å – beyond 7400 Å the second order spectrum starts to overlay the first order.

High resolution (R > ~10,000) shows a limited wavelength range in great detail.

- e.g. Shelyak Lhires (with 2400 l/mm grating) range is ~100 Å wide but tunable across the visual range.

If you are have deep enough pickets, an Echelle will do both!

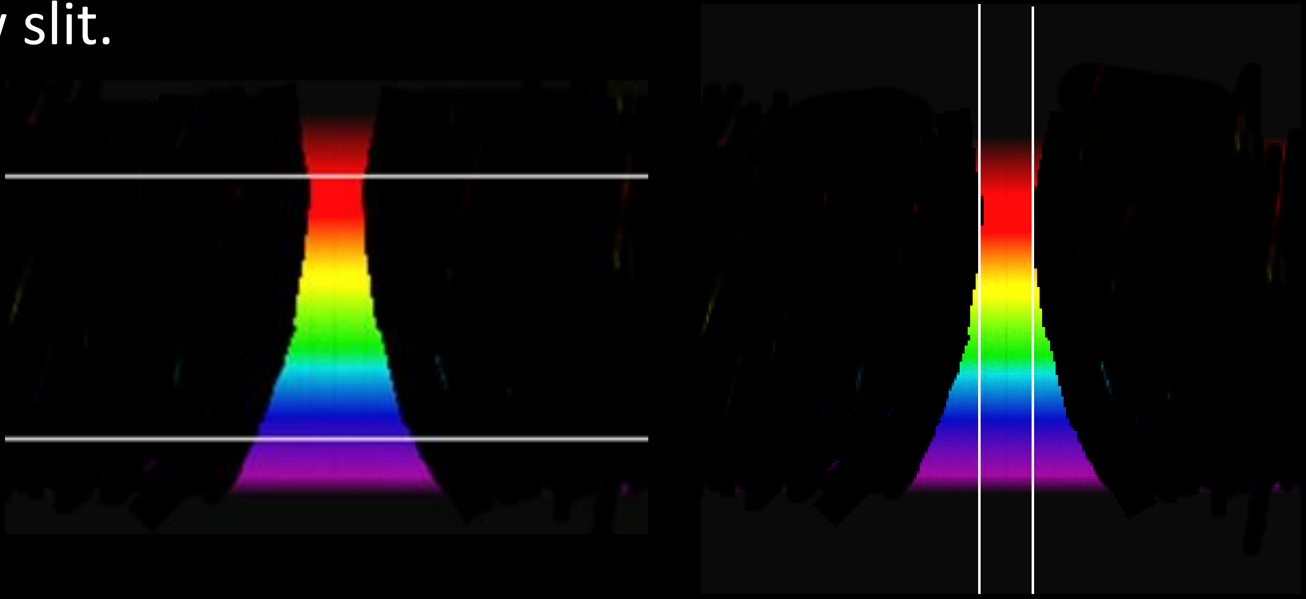
A few tips . . .

I’m not going to say more about the hardware side of spectroscopy but offer a few tips . . . .

- Buy guiding and calibration modules for your spectroscope if these are available, they will greatly increase your productivity.
- You will need to autoguide long exposures so make sure your mount and slit guiding software are up to the job.
- Always put the target on the same pixel in the guide camera as this will give the most consistent processing.
- Don’t change focus between the reference star and the target as this will change the star image size in the slit.

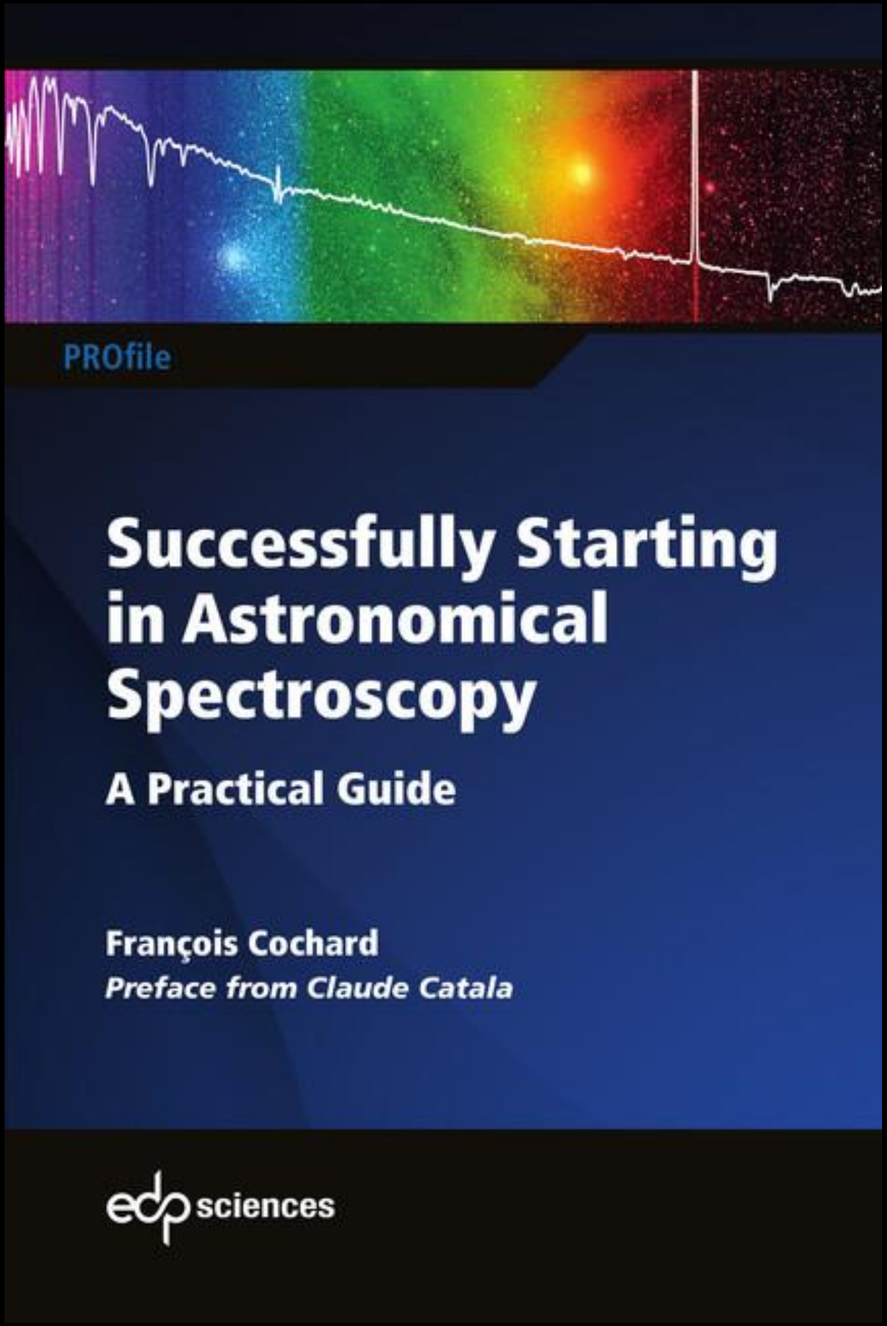
A word of warning

Spectroscopy at low altitudes (air mass > ~2) raises complex issues due to atmospheric and chromatic dispersion of star images and the possibility of wavelength dependent transmission through a narrow slit.



Check out Christian Buil's website to understand the problem and why you should orient the slit at the parallactic angle if possible.
http://www.astrosurf.com/buil/dispersion/atmo.htm

For this reason I tend not to work lower than an air mass of 2.



This is a good practical guide to setting up and using your spectroscope for optimal performance.

It’s a book I wish had been available when I started out in spectroscopy.

Several software packages are available for processing amateur spectra:

- RSpec – easy to use commercial package (Tom Field)
- Visual Spec (VSpec) – basis set of analysis tools (Valérie Desnoux)
- BASS – full range of processing functions (John Paraskeva)
- ISIS – most comprehensive analysis software (Christian Buil)
- Demetra – purpose-built toolkit for Alpy 600 users (Shelyak)
- PlotSpectra – spectral analysis and plotting program (Tim Lester)
- IRAF – professional software, steep learning curve (Linux-based)

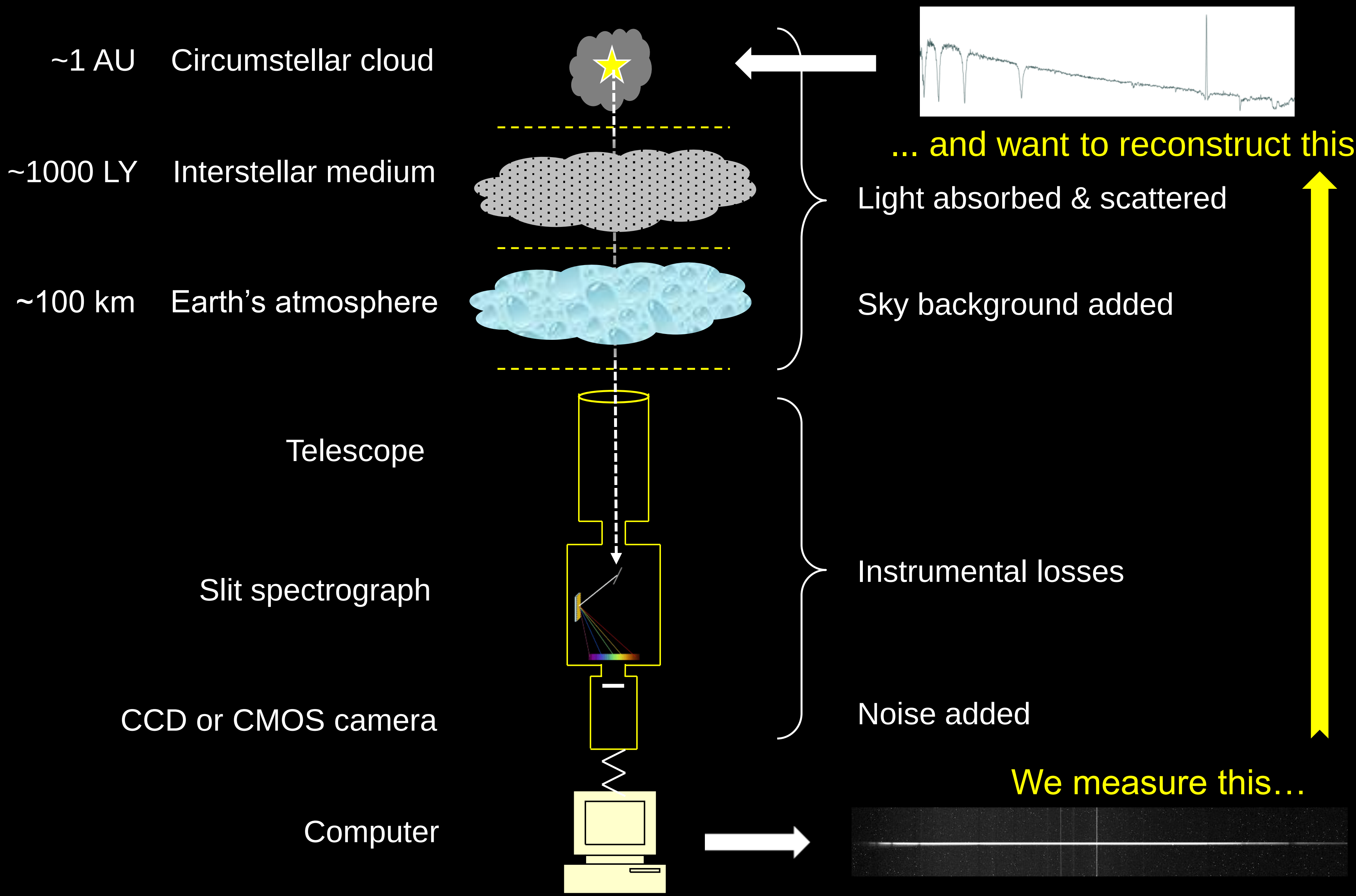
- Many of the examples I will use in the workshop were taken with a LISA spectroscope which records from 3800 to 7400 Å at a spectral resolution of ~1000.

- Its wide optical range makes it easier to demonstrate the various processing steps involved.

- I will often use ISIS software in examples as it is the package I am most familiar with and has the greatest range of useful functionality.

So now let’s look at the problem we are trying to solve . . .

Photon's perilous journey from stellar photosphere to pixel



The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Processing raw 2D spectral images

These have a number of problems and well-established solutions, all familiar to imagers and photometrists:

- Bias or offset signal (ensures pixels are positive) -> bias frame
- Dark signal (noise generated in the camera – scales with exposure and temperature) -> dark frame
- Hot pixels (ditto – scales differently with exposure and temperature) -> hot pixel list
- Pixel non-uniformity (inherent in the chip)
- Vignetting (due to constrictions in the optical path)
- Dust donuts (due to obscuration in the optical path)

-> flat frame

Flat frame – a source of much discussion and debate!

Usually generated with a broad spectrum light source (e.g. tungsten bulb) whose light is directed through the slit.

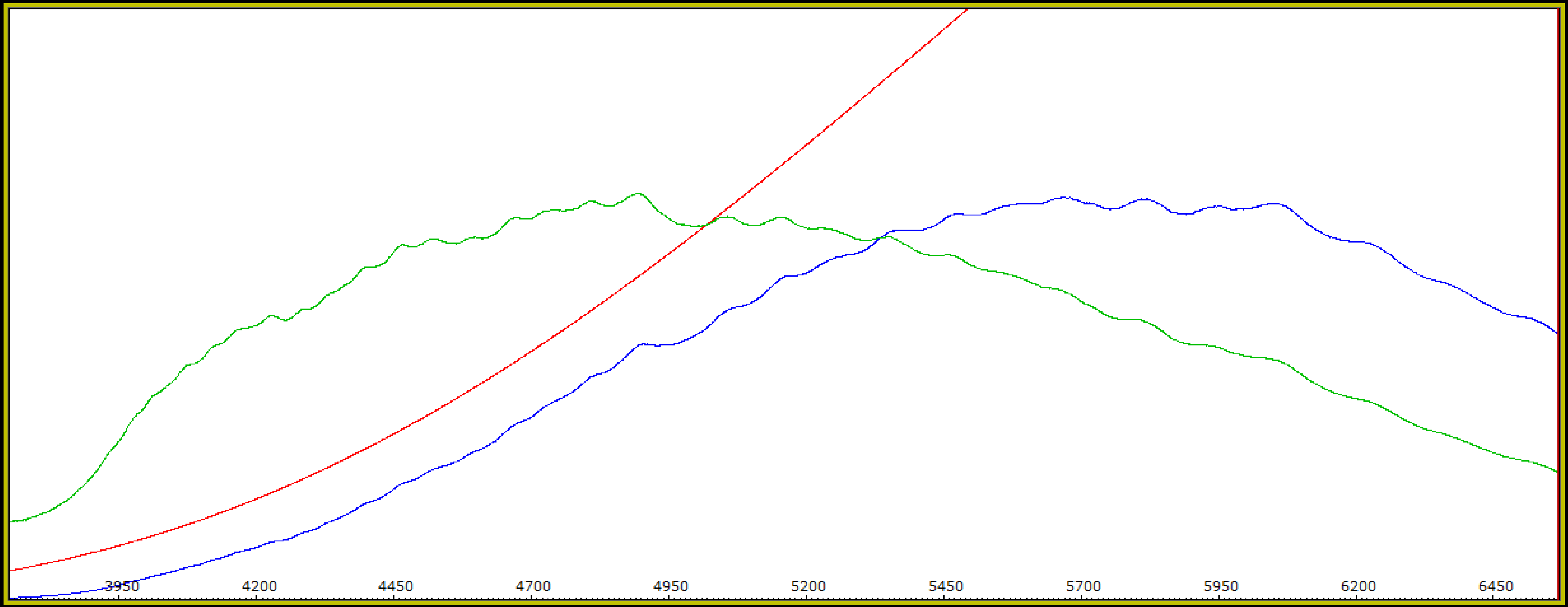
Therefore includes the combined wavelength response of the light source, spectroscope and camera.

Provided the same flat frame is used for all images processed the instrumental response component cancels out in the end.

Flat frames may also be able to correct for camera or chip window interference fringes – see ARAS Forum for more on this.

http://www.spectro-aras.com/forum

Flat frame correction in ISIS



In ISIS version 5.9.3 and earlier the flat lamp profile (blue) is divided by the Planck curve for the 2750K tungsten lamp (red) to compensate for the strong blue end deficit in the flat lamp (green).

From version 5.9.6 onward there is no division by the Planck curve.

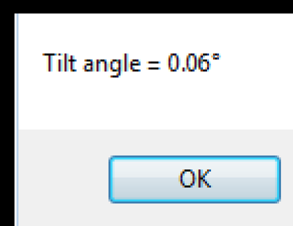
The results in a response profile more sharply peaked in the blue.

Correcting alignment problems

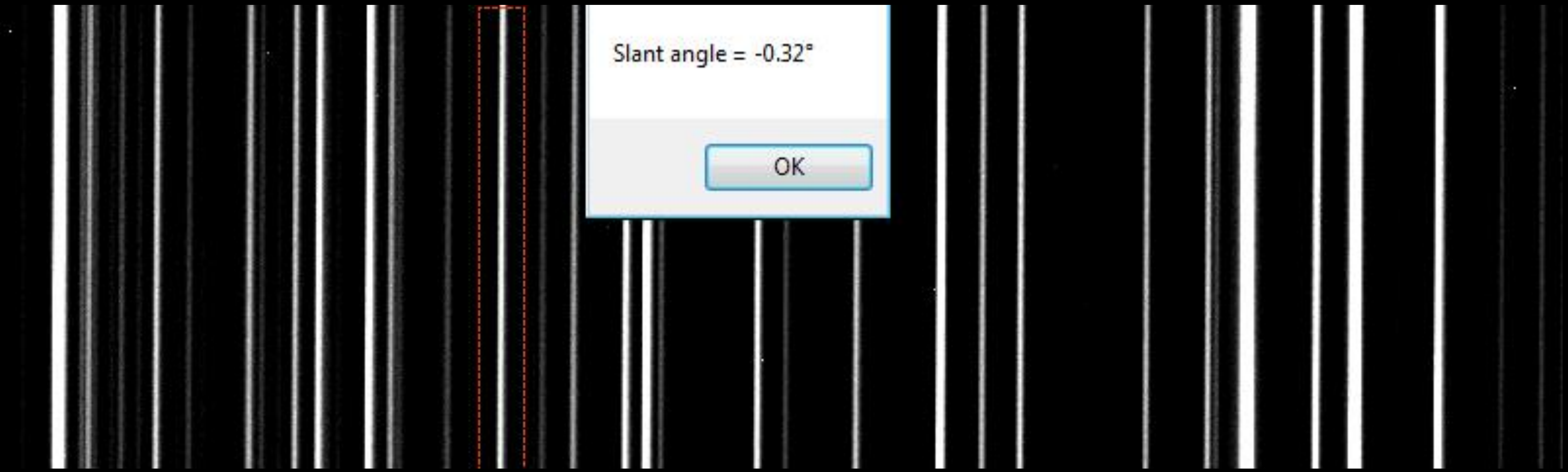
After applying these corrections to the raw spectral images we need to correct for possible misalignments or optical distortions.

These are:

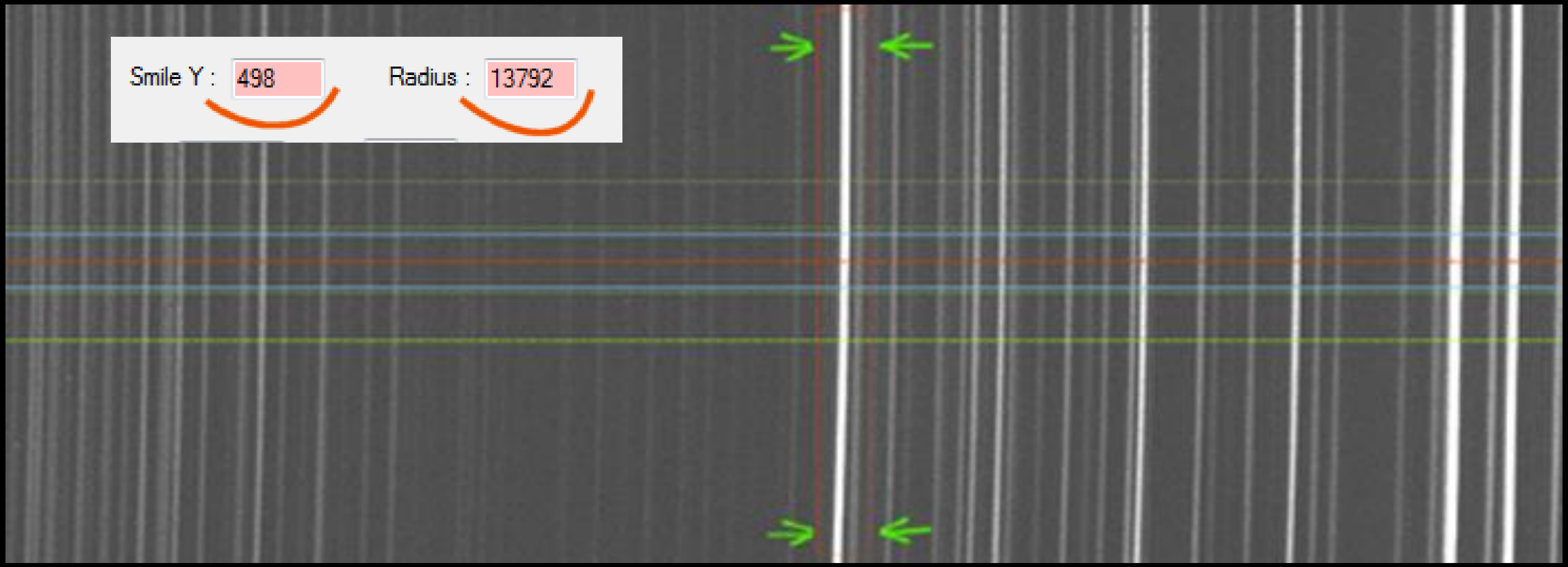
“tilt” – horizontal misalignment of the recorded spectrum with the X-axis of the camera;



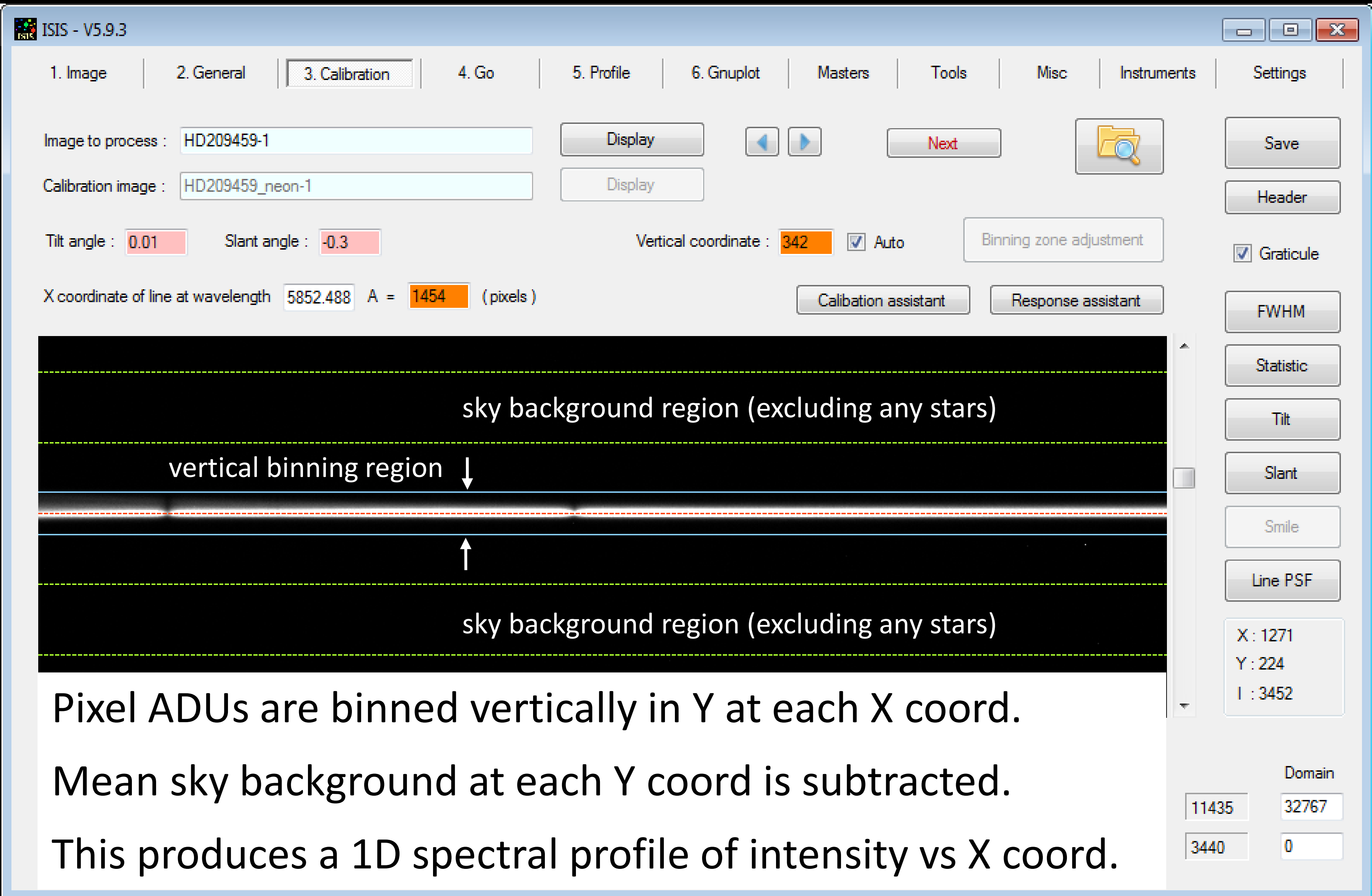
“slant” – vertical misalignment of the slit;



“smile” – optical distortion in the spectroscope.



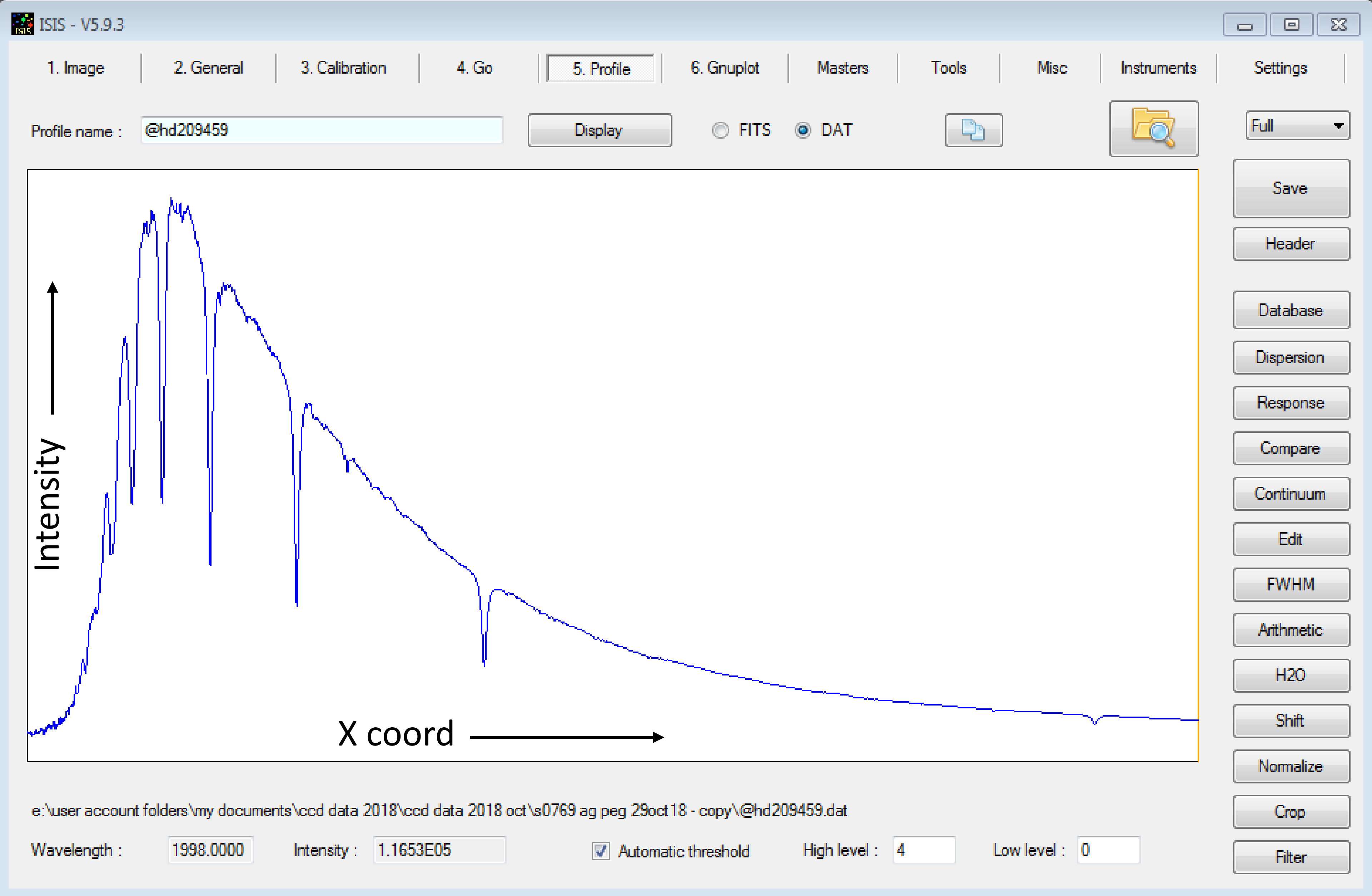
Extracting the spectrum from a 2D spectral image in ISIS



Pixel ADUs are binned vertically in Y at each X coord.

Mean sky background at each Y coord is subtracted.

This produces a 1D spectral profile of intensity vs X coord.



We need to calibrate this 1D spectral profile in terms of wavelength.

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

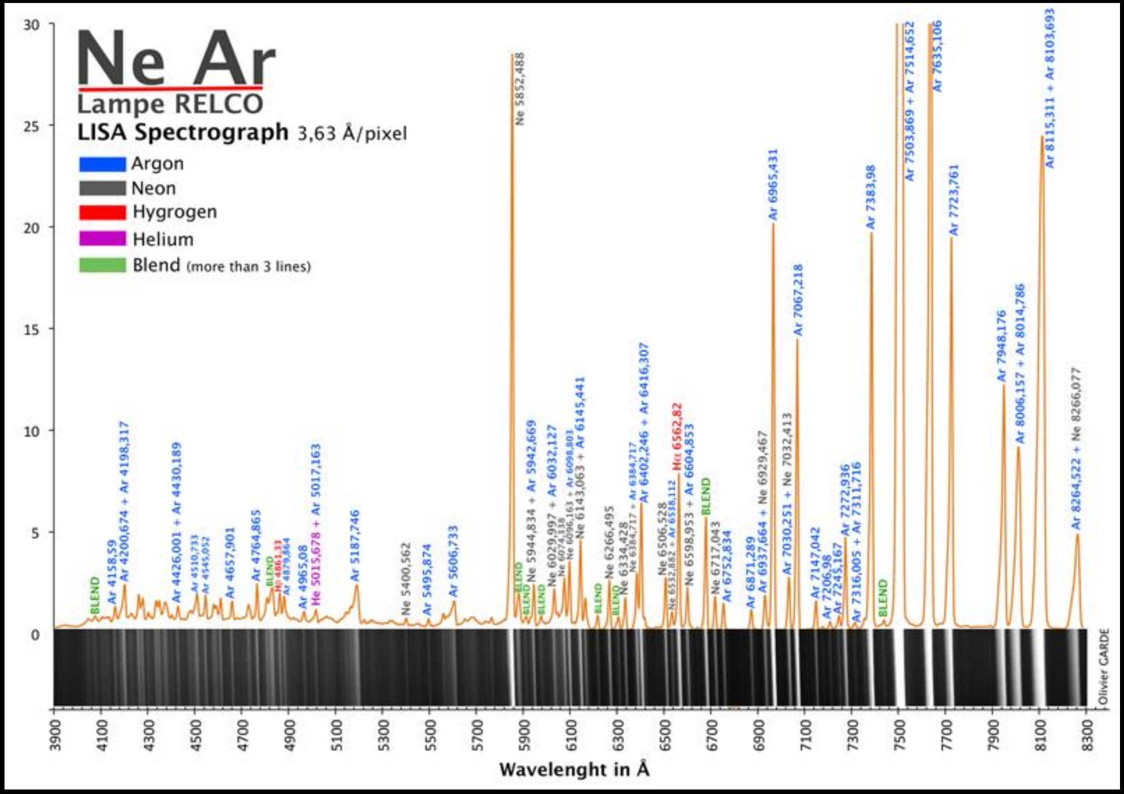
- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Wavelength calibration

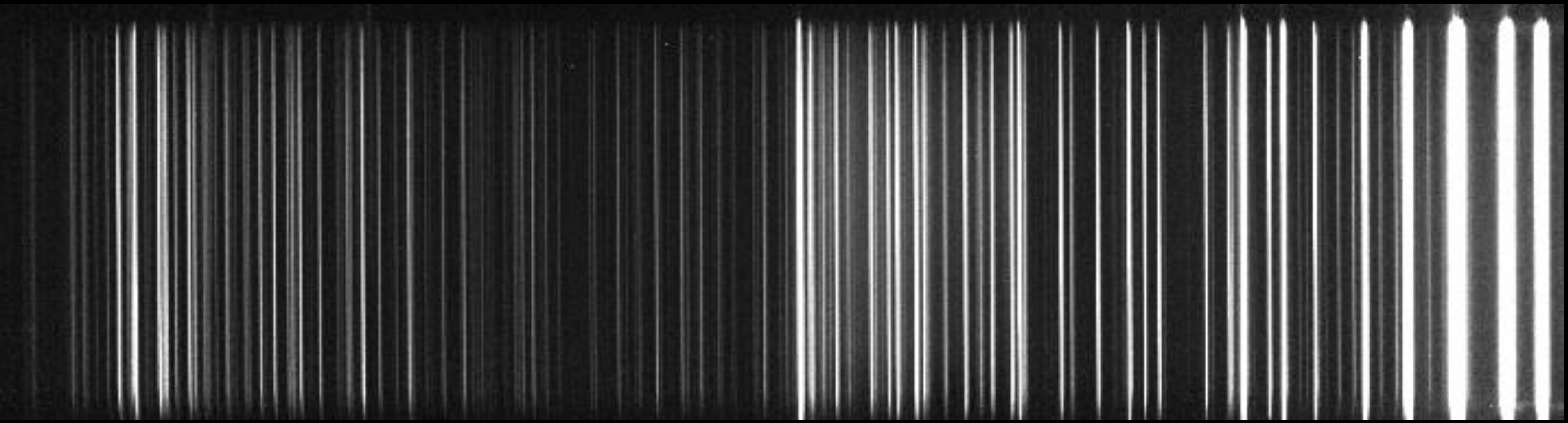
Commercial spectroscopes normally come with a calibration module either as standard or as an optional extra. (Buy it!)

This usually contains a Ne-Ar or Th-Ar light source which produces emission lines with known wavelengths across the spectrum.
https://physics.nist.gov/PhysRefData/ASD/lines_form.html

Light from the calibration lamp is directed through the slit into the spectroscope and imaged with the camera.



Calibration lamp spectrum



The spectroscope objective should be focused to make these lines as sharp as possible in a balanced way across the spectrum.

Make sure you don't saturate the spectral lines.

Tip – you only need to read out the vertical portion of the chip which contains the lamp spectrum – this can save a lot of disk space.

Dispersion equation

Measure X coords of a set of emission lines with known wavelengths.

Fit wavelength difference from linearity with a 3rd or 4th order polynomial in X. e.g. $\lambda = a0 + a1*X + a2*X^2 + a3*X^3 + a4*X^4$

Results from ISIS

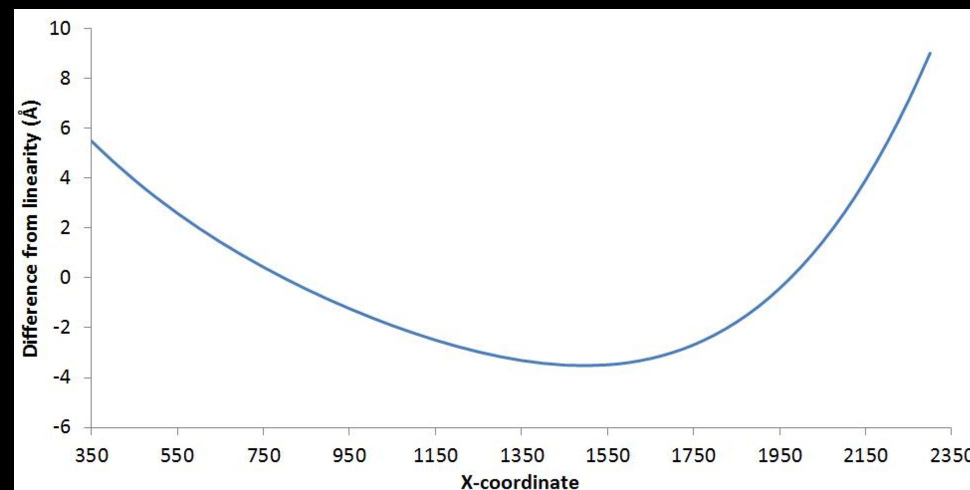
Wavelength fitting error

Line #1 x = 2285.000 lambda = 7383.980 dlambda = -0.028
Line #2 x = 2225.175 lambda = 7272.936 dlambda = 0.068
Line #3 x = 2114.081 lambda = 7067.218 dlambda = -0.003
Line #4 x = 2058.956 lambda = 6965.431 dlambda = -0.066
Line #5 x = 1809.075 lambda = 6506.528 dlambda = 0.004
Line #6 x = 1752.069 lambda = 6402.248 dlambda = 0.030
Line #7 x = 1610.173 lambda = 6143.063 dlambda = -0.009
Line #8 x = 1501.387 lambda = 5944.834 dlambda = 0.053
Line #9 x = 1450.712 lambda = 5852.488 dlambda = -0.016
Line #10 x = 1202.206 lambda = 5400.562 dlambda = -0.062
Line #11 x = 962.280 lambda = 4965.080 dlambda = 0.012
Line #12 x = 915.291 lambda = 4879.864 dlambda = 0.032
Line #13 x = 851.905 lambda = 4764.865 dlambda = -0.023
Line #14 x = 730.602 lambda = 4545.052 dlambda = 0.016
Line #15 x = 517.118 lambda = 4158.590 dlambda = -0.008

Coefficient a4 : 3.777636E-12
Coefficient a3 : -1.487419E-08
Coefficient a2 : 2.678694E-05
Coefficient a1 : 1.79047
Coefficient a0 : 3225.526

Dispersion equation

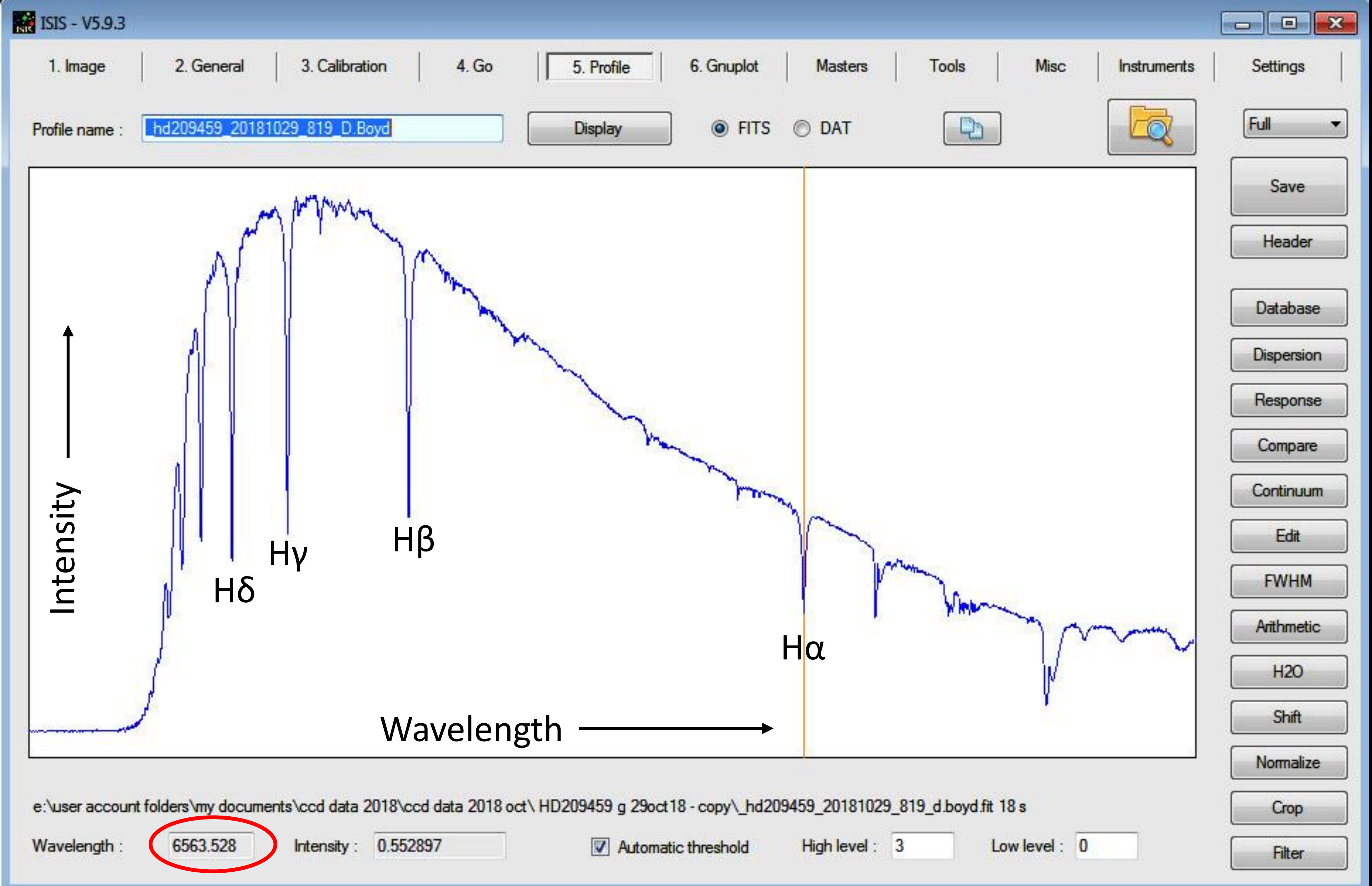
RMS : 0.044354 Å



This is the dispersion equation.

We use it to calibrate the spectrum in terms of wavelength.

Dispersion in Å/pixel.

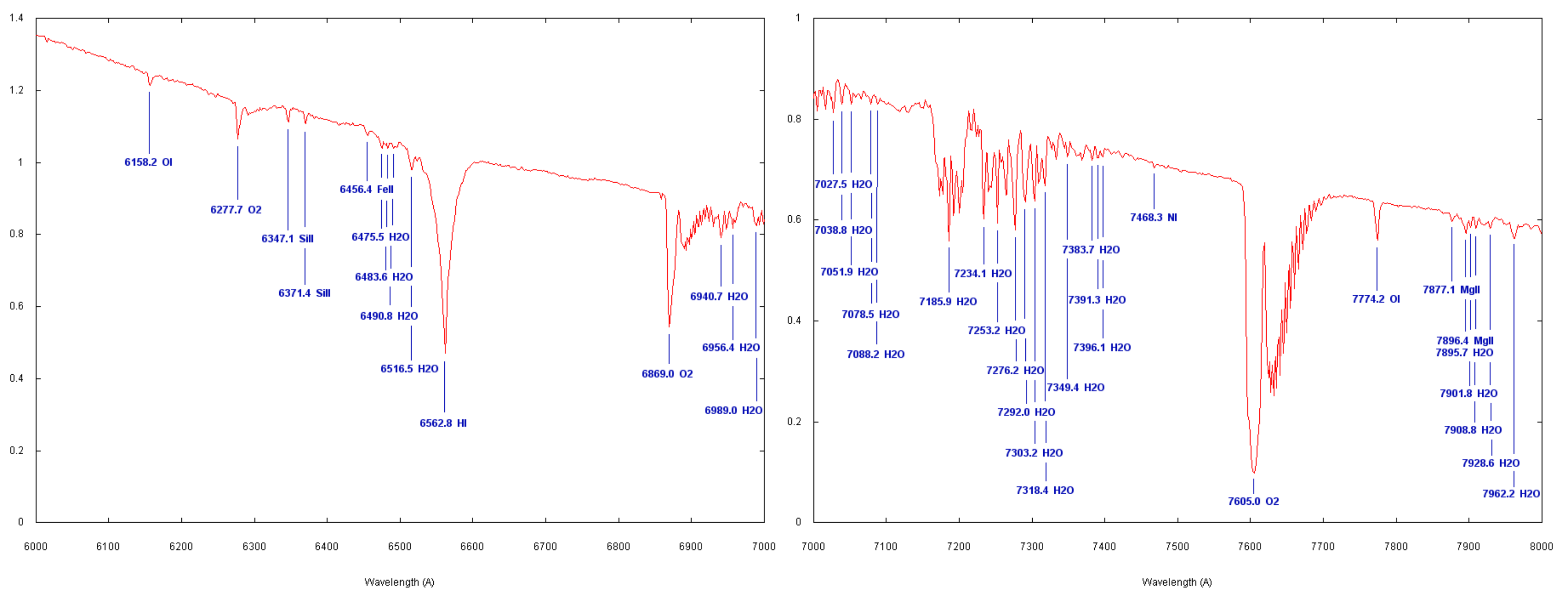


This is the 1D spectral profile now calibrated in wavelength (Å)

Wavelength calibration at high resolution

With a high resolution spectroscope, where few calibration lamp lines may be visible, telluric lines from the atmosphere with known wavelengths may be used as well or instead.

Tellurics can also provide a useful check on your lamp calibration.



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

Good practice in wavelength calibration

Wavelength calibration can change with temperature and/or with mechanical flexure in the spectroscope and camera.

Every time you take a set of target spectra, it is good practice to also take a calibration lamp spectrum and generate a new dispersion equation to calibrate that set of target spectra.

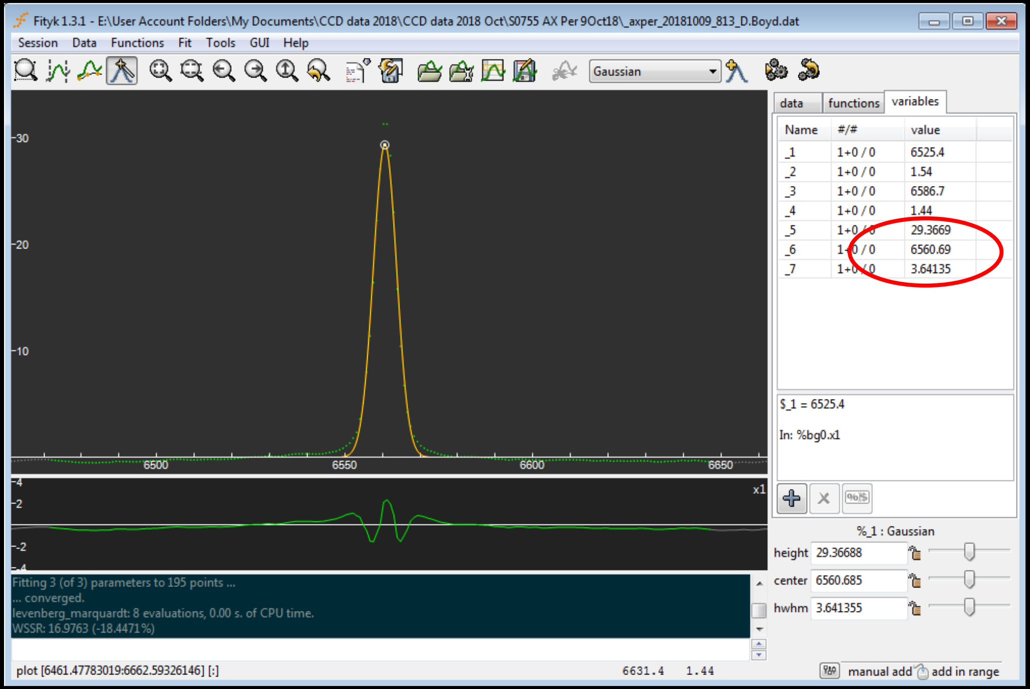
I usually also also take a calibration spectrum after a long series of spectra just as a check that nothing has changed.

If you need the highest accuracy in wavelength calibration, for example when measuring radial velocities, you should take lamp spectra before and after each set of target spectra and average these.

Measuring the wavelength of spectral lines

This Gaussian fit to the Hα line (6562.8 Å) in AX Per gives its wavelength as 6560.7 Å – why?

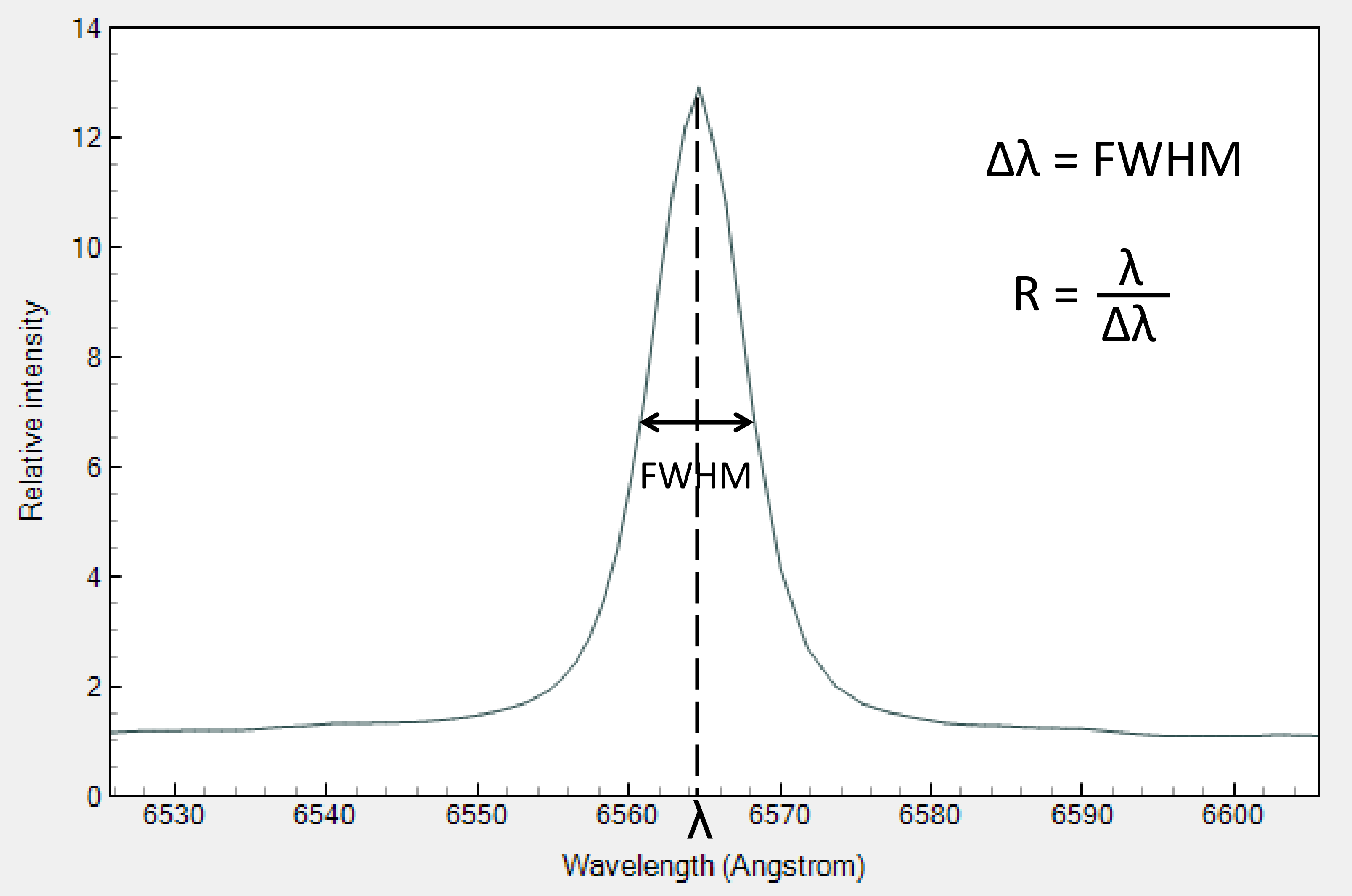
AX Per has a galactic RV of -110 km/s and, at the time the spectrum was recorded, heliocentric RV of +11 km/s.



Together these blue shift the wavelength of the Hα line by 2.2 Å – so we really measure the wavelength of the Hα line as 6562.9 Å.

Wavelengths you measure will be affected by the radial velocity of the star, the heliocentric velocity of the earth, and possibly also dynamics within the stellar photosphere.

Spectral resolution reminder . . .



$$\Delta\lambda = \text{FWHM}$$

$$R = \frac{\lambda}{\Delta\lambda}$$

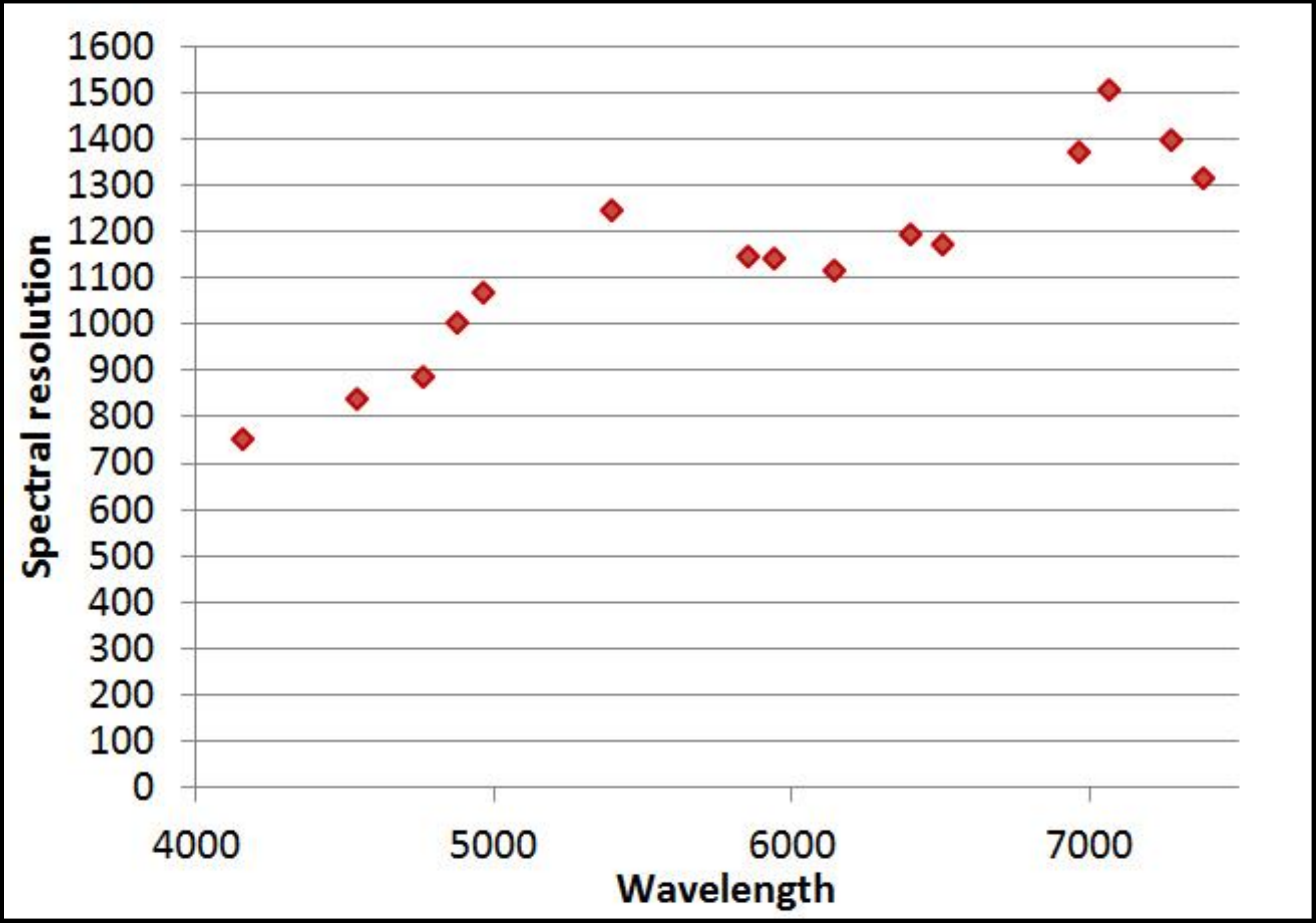
FWHM = 6 Å λ = 6563 Å R = 6563/6 = ~1000

Measuring your spectral resolution

It's an interesting exercise to measure the variation of your spectral resolution with wavelength using the calibration spectrum.

Measure the FWHM of each line in pixels and multiply that by the dispersion in Å/pixel to get Δλ. Then R = λ/Δλ.

You can shift the point of maximum resolution by refocusing the objective lens.



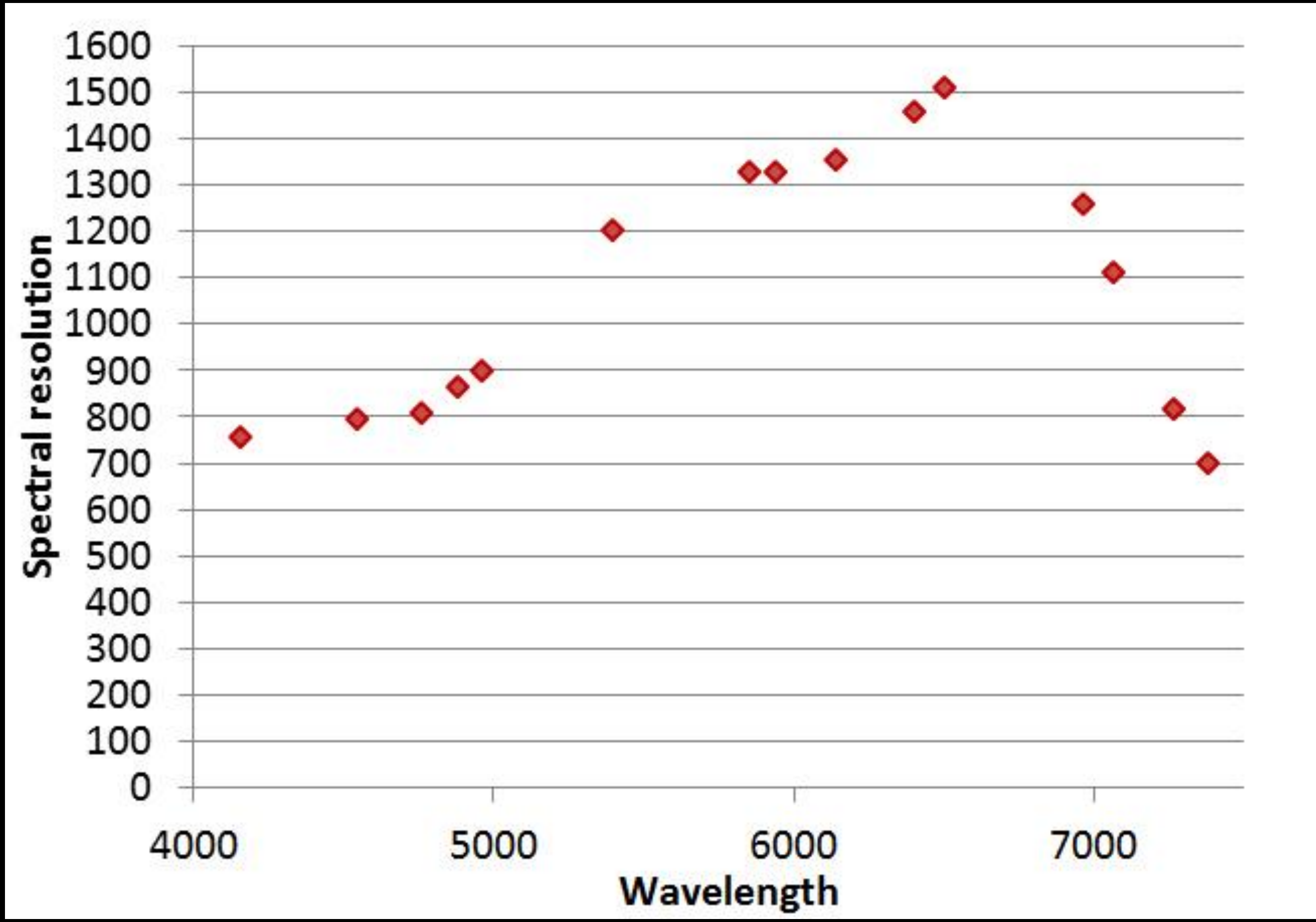
LISA with 23 μm slit

Measuring your spectral resolution

It's an interesting exercise to measure the variation of your spectral resolution with wavelength using the calibration spectrum.

Measure the FWHM of each line in pixels and multiply that by the dispersion in Å/pixel to get $\Delta\lambda$. Then $R = \lambda/\Delta\lambda$.

You can shift the point of maximum resolution by refocusing the objective lens.



LISA with 23 µm slit

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Instrumental and atmospheric losses

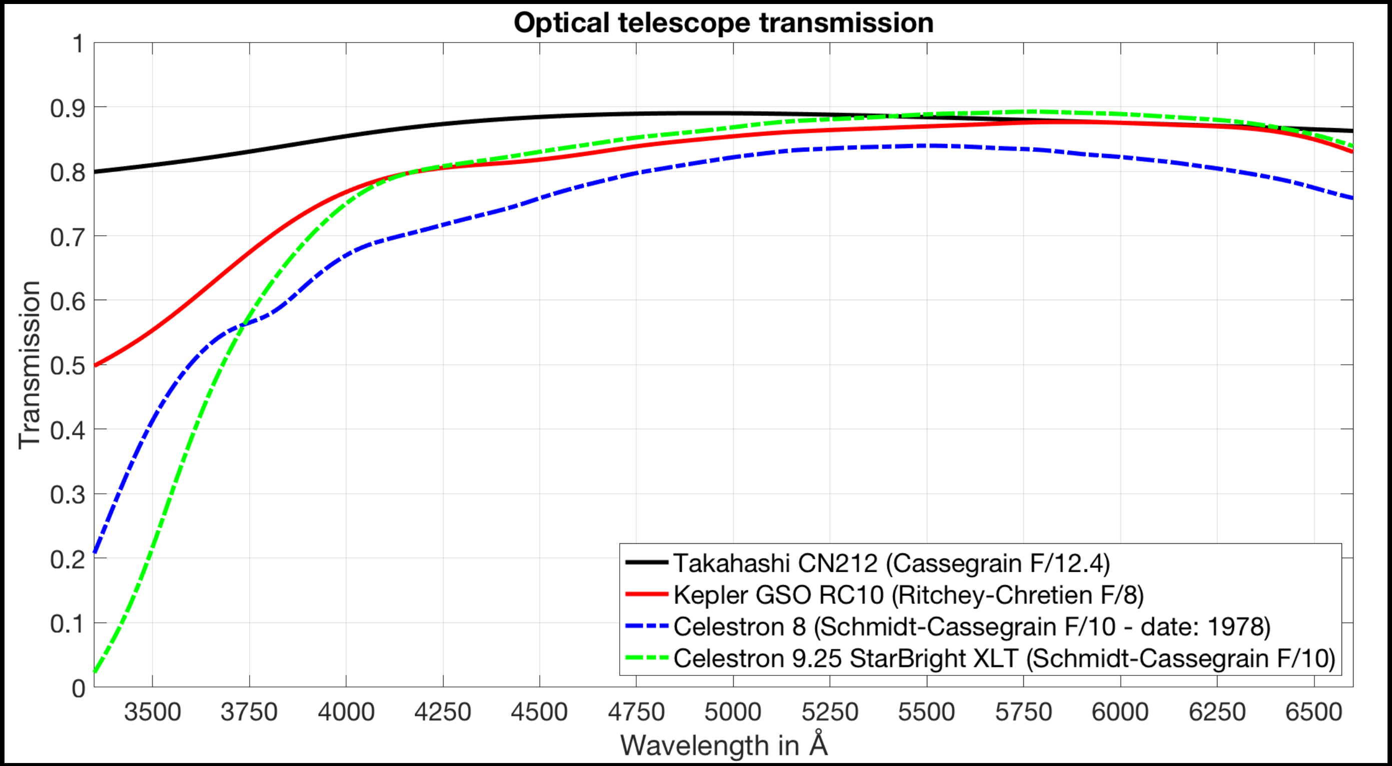
Our wavelength-calibrated spectrum still suffers from two major wavelength-dependent effects which alter the recorded spectral profile :

- losses in the instrument (telescope + spectroscope + camera);
- losses in the atmosphere due to absorption and scattering.

We now need to evaluate and correct for these.

Instrumental losses (1)

We usually assume that telescopes transmit fairly uniformly across the visual spectrum but this is not necessarily true if we are trying to work in the UV, e.g. with Christian Buil's UVEX spectroscope.

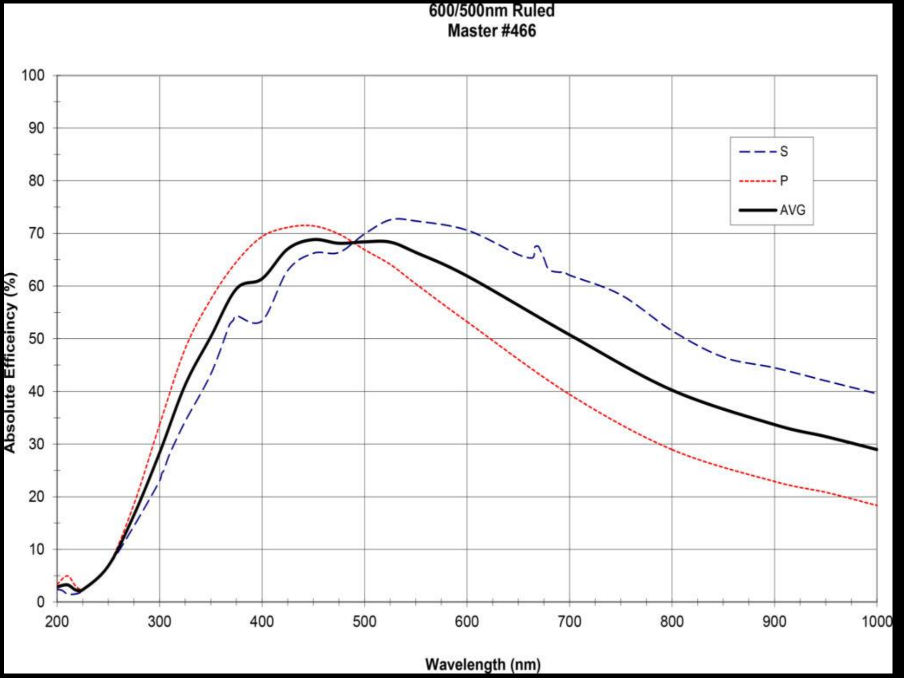


Measured transmittance for various telescopes

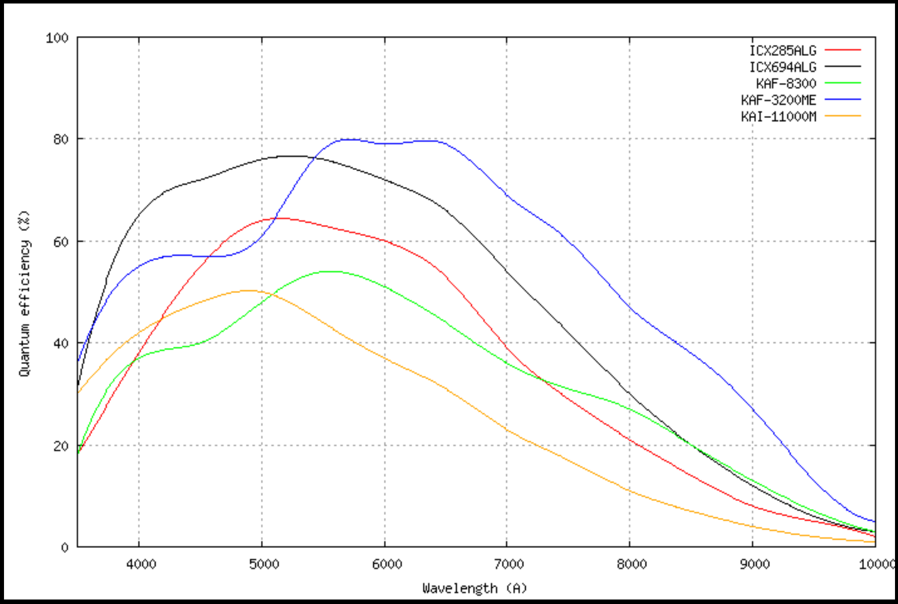
http://www.spectro-aras.com/forum/viewtopic.php?f=45&t=2277#p12402

Instrumental losses (2)

The response of the spectroscope may be available from the supplier – this is a typical grating efficiency curve from Shelyak.



The camera response is often provided by the manufacturer – these are efficiency curves for various CCD chips.



The total throughput including all components may well be below 40% in the centre of the spectrum and even less towards the blue and red ends.

Instrumental losses (3)

To these losses, must be added the loss at the slit which depends on the seeing, slit width, aperture and working focal ratio of the telescope.

e.g. for 3 arcsec seeing (at the zenith):

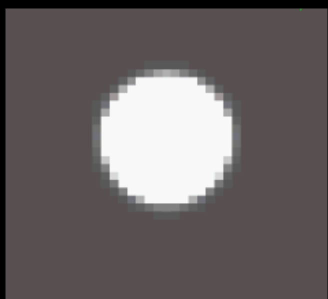
Aperture	Loss at 18μm slit	Loss at 23μm slit	Loss at 35μm slit
200 mm at f/5	16%	10%	2%
300 mm at f/5	35%	24%	6%
400 mm at f/5	48%	41%	16%
200 mm at f/10	48%	41%	16%
300 mm at f/10	64%	56%	35%
400 mm at f/10	72%	68%	48%

There are also UV transmission losses in a reflective slit on glass.

Atmospheric refraction and slit transmission

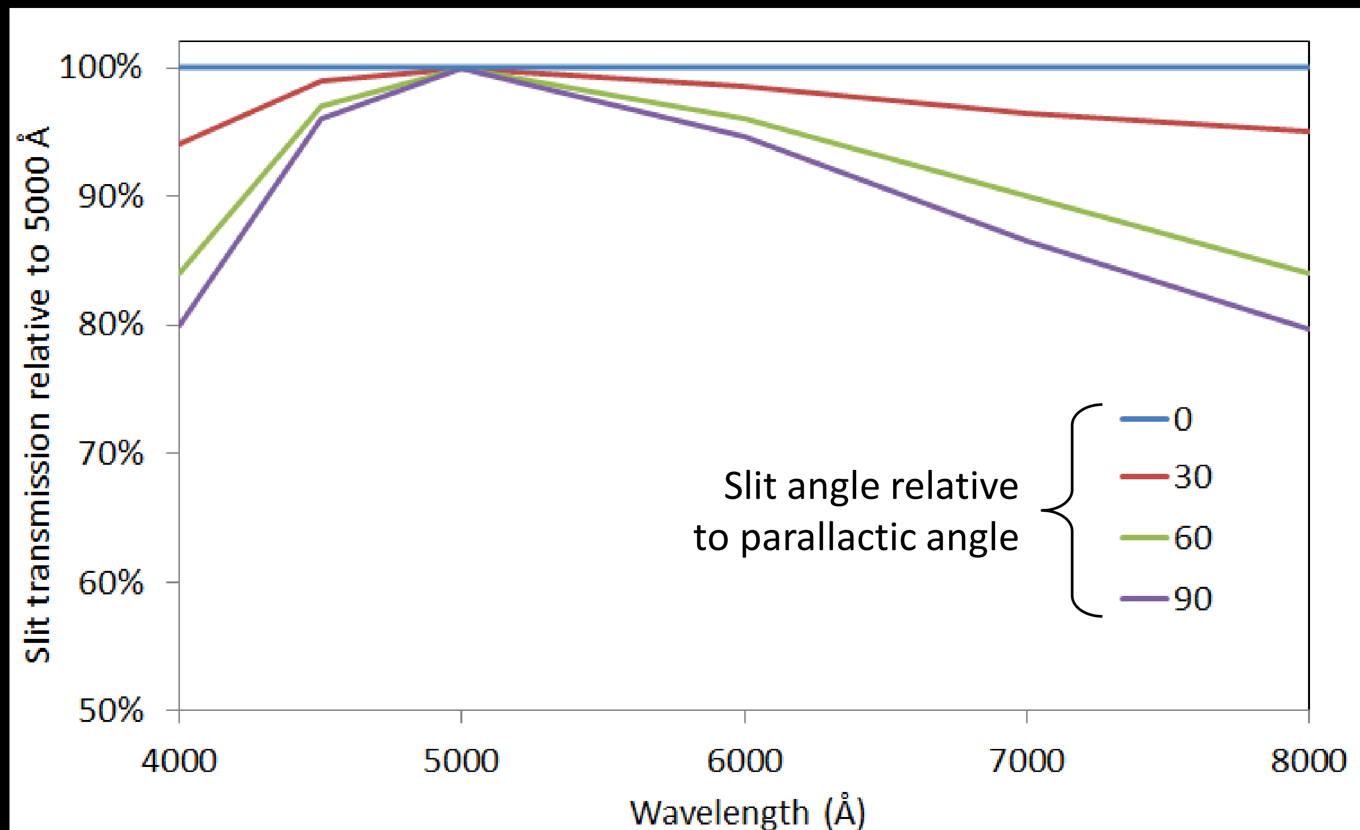
Example with 23µm slit on a 300mm f/5 scope and 3” seeing

At air mass = 2, slit transmission across the spectrum depends on slit orientation relative to the parallactic angle:



Star image at zenith

Star image at airmass = 2



Slit transmission calculator : http://www.caha.es/pedraz/RS/refract_slit.html

Atmospheric losses (1)

Atmospheric extinction has two principal causes:

- Aerosol scattering including dust and water vapour;
- Rayleigh scattering from atoms and molecules.

There is also a small amount of absorption due to ozone between 5000 and 7000 A and to water absorption features.

Clouds, when present, are considered to be “grey” scatterers.

Contrails from aircraft are an increasing problem and one which has not yet been thoroughly analysed.

C. W. Stubbs et al., *Towards More Precise Survey Photometry for PanSTARRS and LSST: Measuring Directly the Optical Transmission Spectrum of the Atmosphere*, PASP, 119, 1163 (2007)
https://iopscience.iop.org/article/10.1086/522208/pdf

Atmospheric losses (2)

Aerosol scattering is relatively uniform across the spectrum rising slowly at shorter wavelengths approximately as λ^{-1}.

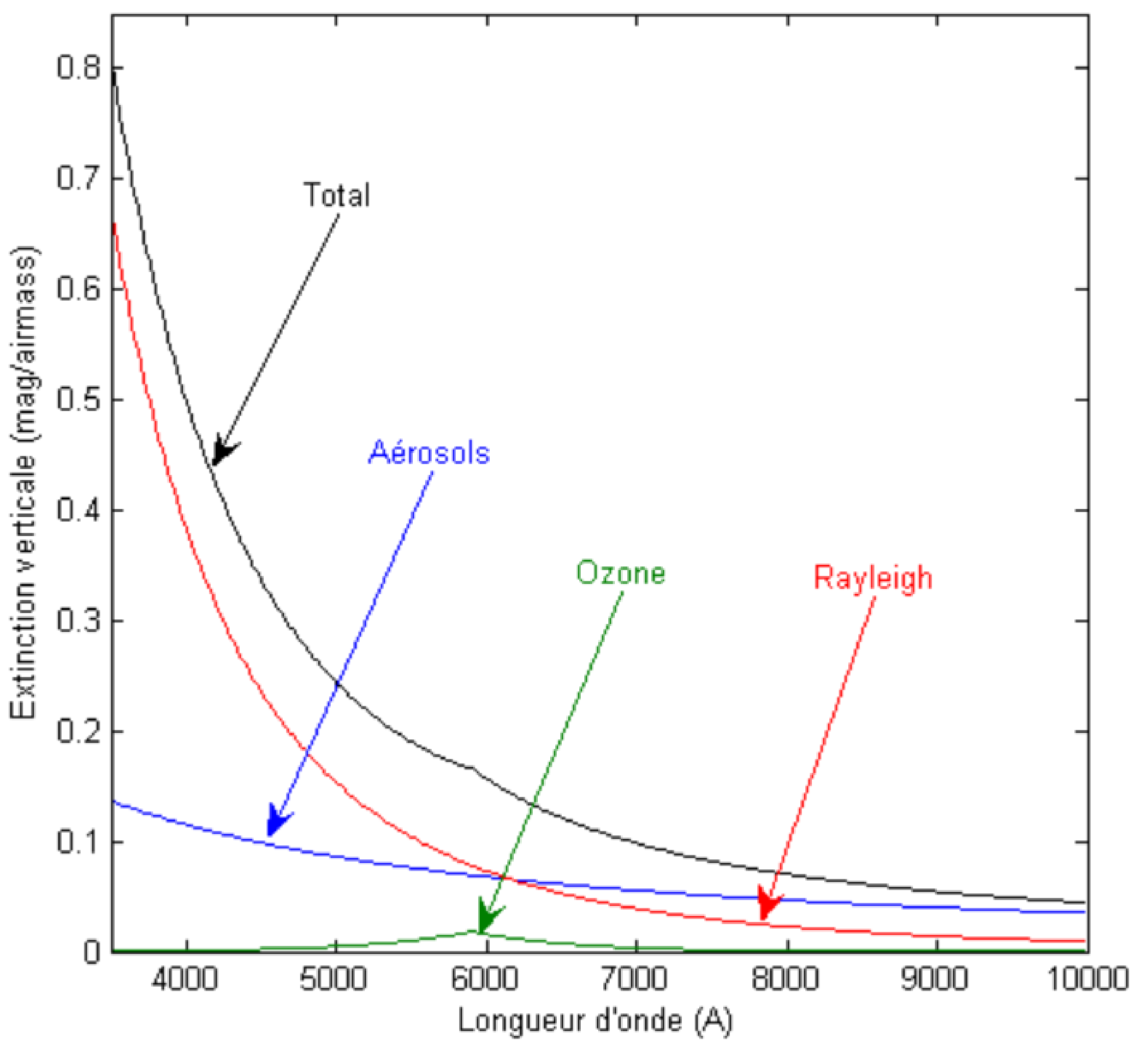
It is the dominant cause of extinction at wavelengths longer than about 6000 Å.

The amount of aerosol scattering can vary greatly in time and direction depending on the aerosol content of the atmosphere.

Rayleigh scattering increases very rapidly at shorter wavelengths as λ^{-4} and dominates at the blue end of the spectrum but remains relatively constant at a given site.

In photometry, correction for these effects is through the first and second order extinction coefficients respectively.

Atmospheric losses (3)



Extinction verticale calculée pour Toulouse (h=0.2 km) par une nuit claire d'hiver (AOD=0.07).

Atmospheric extinction from different sources vs wavelength.

(calculated by Christian Buil for a clear winter's night in Toulouse)

Calculating instrumental and atmospheric losses

In the professional world instrumental and atmospheric losses are measured separately and corrections applied sequentially.

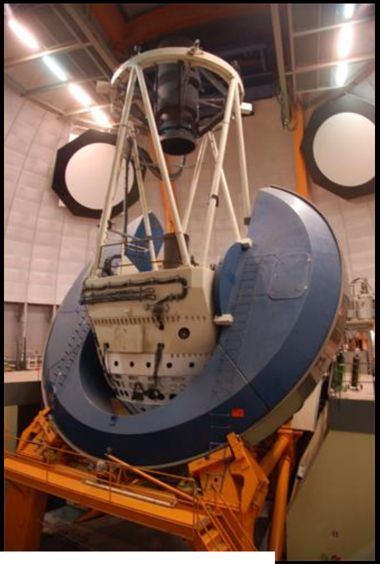
Instrumental losses are generally assumed to be stable over an extended period while atmospheric losses have to be calculated for each observation.

Knowing the instrumental and atmospheric losses, or response profiles, the true spectrum of the star can be calculated from:

True spectrum = Observed spectrum / (Instrumental response x atmospheric response)

In the amateur world, these losses are usually measured and corrected together – but first let's see how the pros do it.

Measuring instrumental losses at Cerro Tololo Observatory

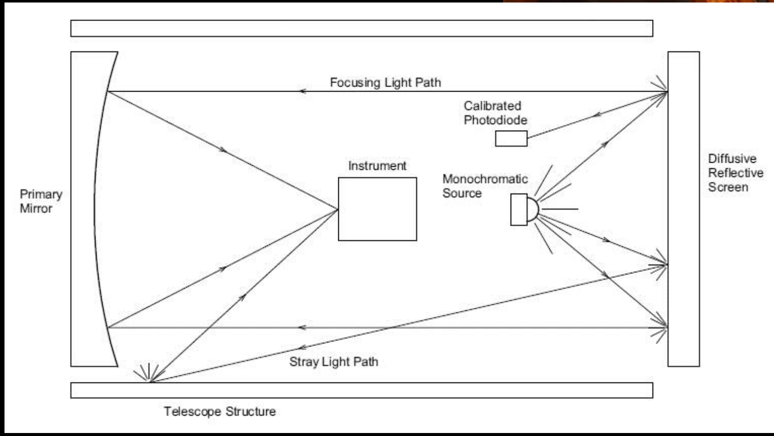


Light from a tunable laser is projected onto the flat-field screen in the 4-m Blanco telescope dome.

The flux reflected into the instrument from the screen is measured with a NIST-calibrated photodiode and compared to the flux detected by the instrument.

Measuring at a succession of wavelengths gives the system throughput as a function of wavelength.

This is based on the calibrated photodiode as the fundamental reference.



C. W. Stubbs et al., *Preliminary Results from Detector-Based Throughput Calibration of the CTIO Mosaic Imager and Blanco Telescope Using a Tunable Laser*, ASP Conference Series, 364, 373 (2007)
https://arxiv.org/pdf/astro-ph/0609260.pdf

Measuring atmospheric losses (1)

Professional observatories are usually located at high altitude sites with photometric observing conditions.

Under these conditions the transmission properties of the atmosphere are relatively well understood and can usually be modelled reliably.

Common practice is to measure spectrophotometric stars with accurately known spectral energy distributions (SED) at different air masses during the night.

These data, together with known instrumental losses, are used to calculate air mass and wavelength dependent atmospheric losses.

C. W. Stubbs et al., *Toward More Precise Survey Photometry for PanSTARRS and LSST: Measuring Directly the Optical Transmission Spectrum of the Atmosphere*, PASP, 119, 1163 (2007)
https://iopscience.iop.org/article/10.1086/522208/pdf

Measuring atmospheric losses (2)

Aerosol Optical Depth (AOD) measures the extinction of light in the atmosphere by dust and haze.

This can vary from 0.01 (very dry) to 0.4 (very moist).

Normal range at low altitude in temperate regions is 0.07 in winter to 0.21 in summer.

AOD can be used to model atmospheric extinction and ISIS provides a method of implementing this described at
http://www.astrosurf.com/buil/atmosphere/transmission.htm
http://www.astrosurf.com/buil/instrument_response_us/

However application of this method really requires photometric conditions (c.f. all-sky photometry) and orienting the slit at the parallactic angle.

Correcting for instrumental and atmospheric losses (1)

As amateurs observing from near our homes, we rarely experience such photometric conditions (for me a handful of times per year) so we need to find another approach.

It is usually impossible to separately measure the instrumental and atmospheric responses so these are measured together.

A commonly used method involves observing the spectrum of a reference star close to the target star whose true exo-atmospheric spectral energy distribution (SED) is already known.

Correcting for instrumental and atmospheric losses (2)

We saw earlier that:

True spectrum = Observed spectrum / Response profile

where the response profile includes both instrumental and atmospheric losses.

From the observed spectrum of the reference star, and knowing its true spectrum, we find the combined instrumental and atmospheric response profile from:

Response profile =
Observed reference star spectrum / True reference star spectrum

Correcting for instrumental and atmospheric losses (3)

We choose a reference star at the same altitude, and hence the same air mass, as our target (AG Peg) so it will experience the same atmospheric loss.

The stars should also be close to each other in azimuth to mitigate against any directional variation in atmospheric extinction or differential slit losses through slit rotation.

Ideally we should use a wide slit for these measurements but it is usually assumed that the reference and target stars experience the same (small) slit losses so the effect should cancel out.

Longer exposures also help to mitigate the issue of slit losses by averaging the effect of guiding imperfections.

Choosing a reference star (1)

The library of stellar spectra most often used by amateurs as a source of reference stars for atmospheric correction is the MILES library.

The library is available at http://miles.iac.es/ and is described in
P. Sanchez-Blazquez et al., *Medium-resolution Isaac Newton Telescope library of empirical spectra,* Monthly Notices of the Royal Astronomical Society, 371, 2, 703 (2006)
http://articles.adsabs.harvard.edu/pdf/2006MNRAS.371..703S
A more recent paper which updates this is
J. Falcon-Barroso et al., *An updated MILES stellar library and stellar population models*, Astronomy & Astrophysics, 532, A95 (2011)
https://www.aanda.org/articles/aa/pdf/2011/08/aa16842-11.pdf

The library contains 985 measured relative flux spectra corrected for atmospheric and interstellar extinction with telluric lines removed.

FWHM of the spectra at all wavelengths is consistently ~2.5 Å.

Choosing a reference star (2)

The ISIS software comes with a version of the MILES database in which the spectra have been reddened so they correspond to the exo-atmospheric spectra which we need for atmospheric correction.

Ideally only stars with small values of E(B-V) (<~0.1) should be used for atmospheric correction to mitigate any inaccuracy in the reddening correction.

You may want to adjust the resolution of the MILES spectrum if it is higher to match that of your spectra.

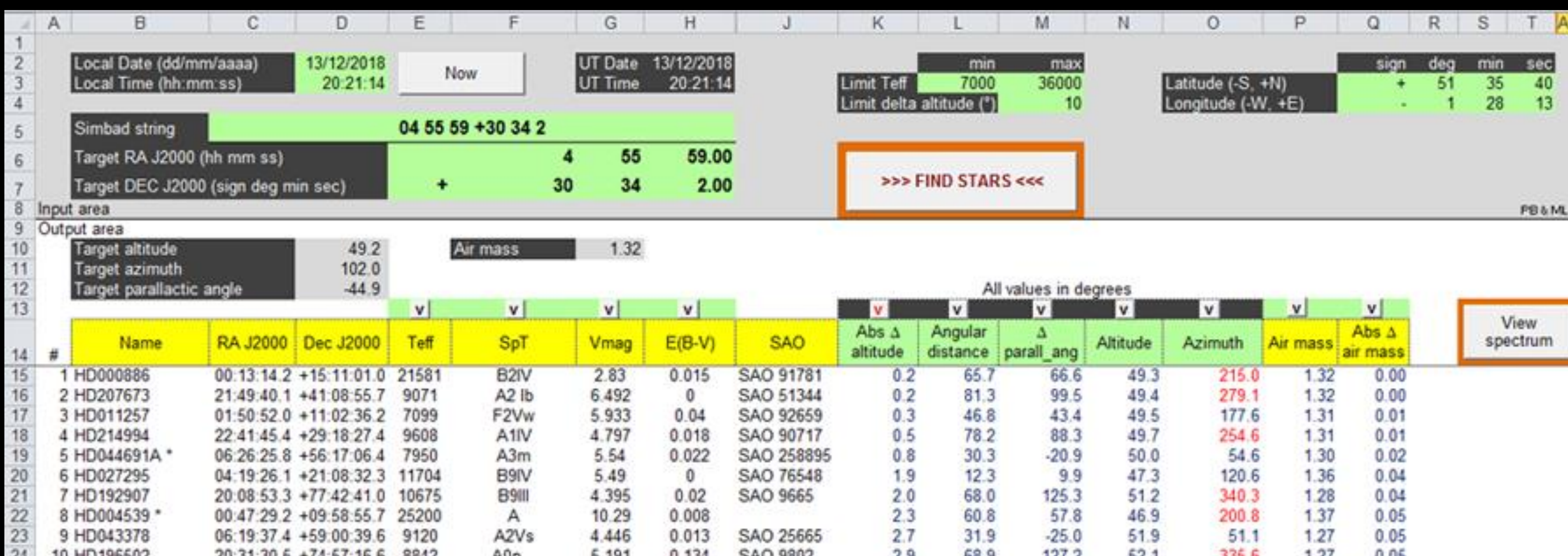
Spectra in the MILES library available from http://miles.iac.es/ are normalised to unity around 5300 Å.

Spectra in the MILES library provided with the ISIS download are mostly normalised to unity around 6700 Å.

Choosing a reference star (3)

Paolo Berardi and Marco Leonardi have created an Excel spreadsheet to locate a MILES star at a suitable altitude and azimuth.
This is available on the ARAS Forum at
http://www.spectro-aras.com/forum/viewtopic.php?f=8&t=941

You enter the time of observation and RA and Dec of your target and the spreadsheet lists possible reference stars with increasing altitude separation from the target.



Local Date (dd/mm/aaaa) 13/12/2018
Local Time (hh:mm:ss) 20:21:14
Now
UT Date 13/12/2018
UT Time 20:21:14

	min	max
Limit Teff	7000	36000
Limit delta altitude (°)		10

	sign	deg	min	sec
Latitude (-S, +N)	+	51	35	40
Longitude (-W, +E)	-	1	28	13

Simbad string 04 55 59 +30 34 2
Target RA J2000 (hh mm ss) 4 55 59.00
Target DEC J2000 (sign deg min sec) + 30 34 2.00

>>> FIND STARS <<<

Input area
PB & ML
Output area

Target altitude 49.2
Target azimuth 102.0
Target parallactic angle -44.9
Air mass 1.32

All values in degrees

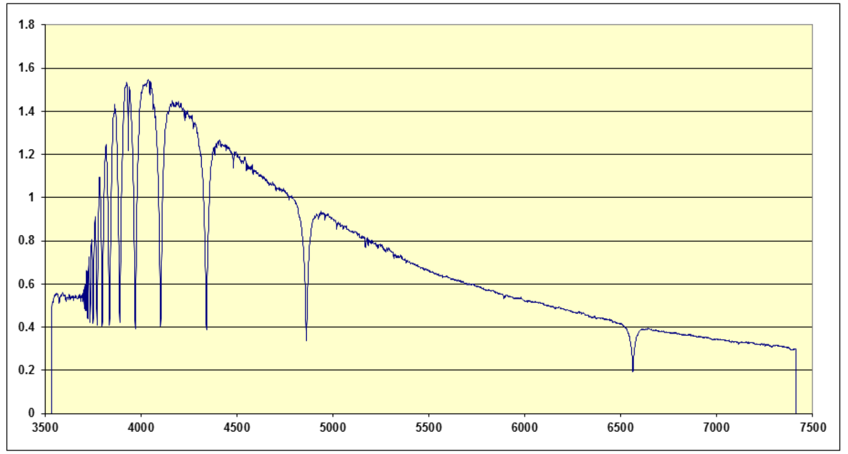
View spectrum

#	Name	RA J2000	Dec J2000	Teff	SpT	Vmag	E(B-V)	SAO	Abs Δ altitude	Angular distance	Δ parall_ang	Altitude	Azimuth	Air mass	Abs Δ air mass
1	HD000886	00:13:14.2	+15:11:01.0	21581	B2IV	2.83	0.015	SAO 91781	0.2	65.7	66.6	49.3	215.0	1.32	0.00
2	HD207673	21:49:40.1	+41:08:55.7	9071	A2 Ib	6.492	0	SAO 51344	0.2	81.3	99.5	49.4	279.1	1.32	0.00
3	HD011257	01:50:52.0	+11:02:36.2	7099	F2Vw	5.933	0.04	SAO 92659	0.3	46.8	43.4	49.5	177.6	1.31	0.01
4	HD214994	22:41:45.4	+29:18:27.4	9608	A1IV	4.797	0.018	SAO 90717	0.5	78.2	88.3	49.7	254.6	1.31	0.01
5	HD044691A *	06:26:25.8	+56:17:06.4	7950	A3m	5.54	0.022	SAO 258895	0.8	30.3	-20.9	50.0	54.6	1.30	0.02
6	HD027295	04:19:26.1	+21:08:32.3	11704	B9IV	5.49	0	SAO 76548	1.9	12.3	9.9	47.3	120.6	1.36	0.04
7	HD192907	20:08:53.3	+77:42:41.0	10675	B9III	4.395	0.02	SAO 9665	2.0	68.0	125.3	51.2	340.3	1.28	0.04
8	HD004539 *	00:47:29.2	+09:58:55.7	25200	A	10.29	0.008		2.3	60.8	57.8	46.9	200.8	1.37	0.05
9	HD043378	06:19:37.4	+59:00:39.6	9120	A2Vs	4.446	0.013	SAO 25665	2.7	31.9	-25.0	51.9	51.1	1.27	0.05
10	HD196502	20:31:30.5	+74:57:16.6	8842	A0p...	5.191	0.134	SAO 9802	2.9	68.9	127.2	52.1	335.6	1.27	0.05

Choosing a reference star (4)

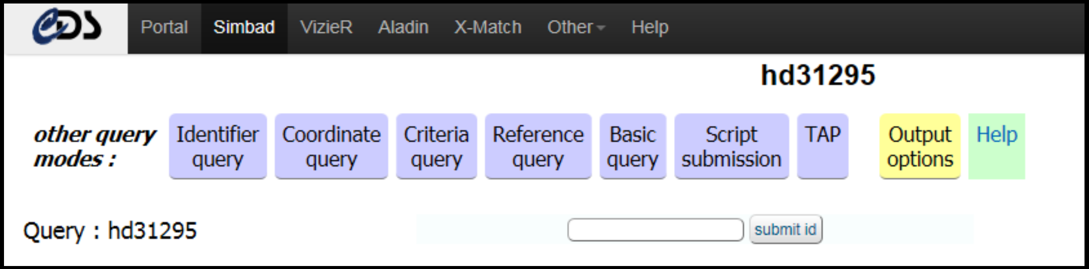
It is best to choose a main sequence star with a spectral type A or B as these have a smooth continuum with relatively few lines plus deep Balmer absorption lines useful for checking wavelength calibration.

Name	Spectrum	RA	Dec	E(B-V)	SpT	Teff	logg	[Fe/H]	Vmag
HD031295	s0166	04:54:53.7	+10:09:02.9	0.1	A0V	8990	4.08	-0.89	4.656



Also check that the spectrum of the star looks reasonable as there are a few stars in the library with “unusual” spectra (e.g. HD216916).

As a final check, look the star up in Simbad to make sure the data in the spreadsheet (taken from the MILES library) is correct.



Choosing a reference star (5)

If you cannot find a suitable star in the MILES library, but you really know the true spectral type of your target, and it is not heavily reddened, and has similar metallicity, then you can use a spectrum of that spectral type from the Pickles Stellar Spectral Flux Library:
http://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/pickles-atlas

These are synthesised spectra which represent average spectra of each spectral type and have no interstellar extinction.

Choosing a reference star (6)

Other libraries of stellar spectra include

the Jacoby-Hunter-Christian Atlas:
http://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/jacoby-hunter-christian-atlas

the ELODIE archive of high resolution spectra:
http://atlas.obs-hp.fr/elodie/

The latter is particularly suitable for users of high resolution spectroscopes such as the Lhires and Echelle.

Read the papers written by the developers to understand the properties of each library and in particular whether they have been corrected for interstellar extinction.

Note that some libraries such as MILES say they are flux calibrated. This often means that they have consistent relative flux across the spectra, not that the spectra are calibrated in terms of absolute flux.

Choosing a reference star (7)

A useful resource if you are trying to find the spectral type of a star is the Catalogue of Stellar Spectral Classifications (Skiff, 2009-2016) in Vizier at
http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=B/mk

B/mk/mktypes Catalogue of Stellar Spectral Classifications (Skiff, 2009-2016) 20
Post annotation The catalog of MK Spectral Types (Version 2014-May) *(888588 rows)*

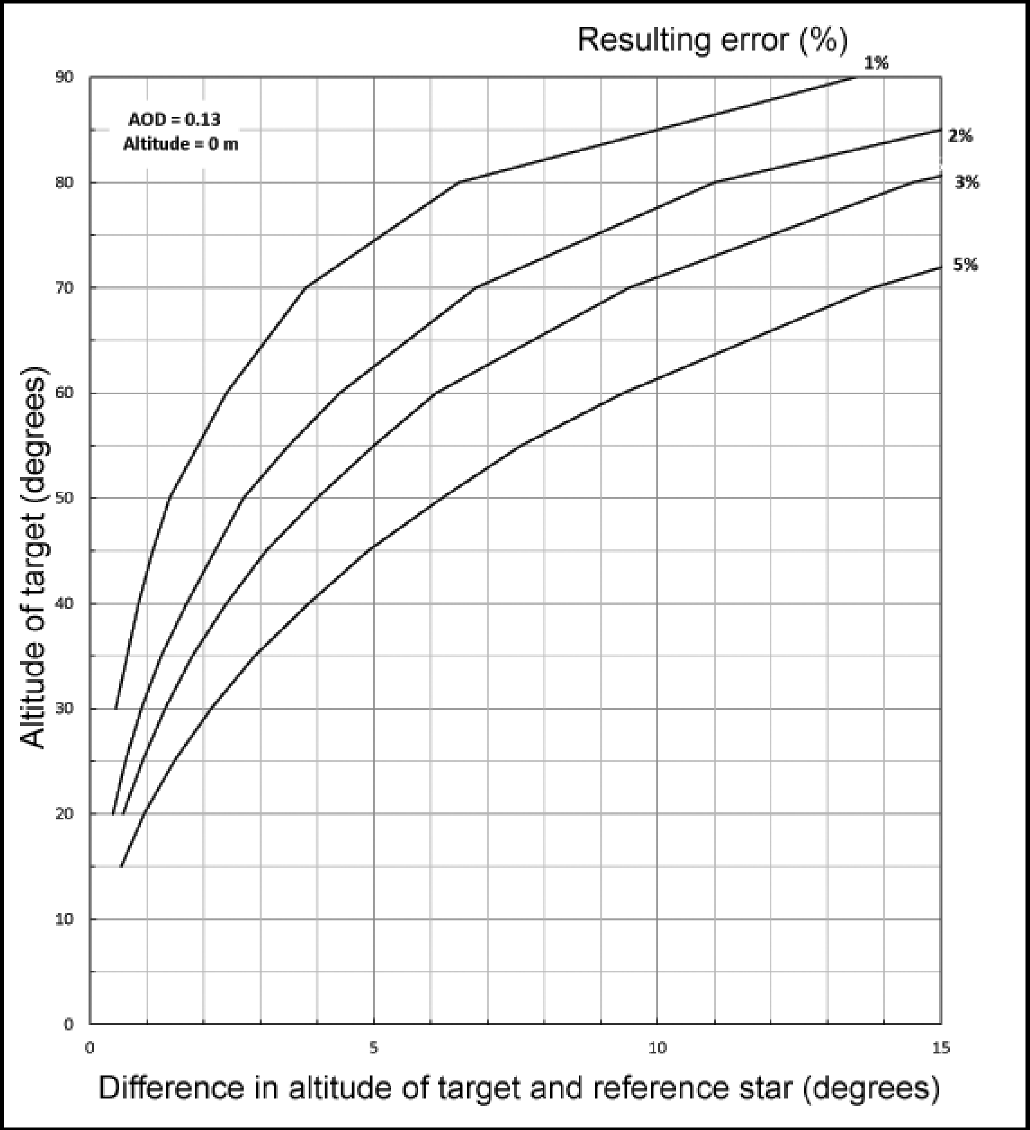
start AladinLite plot the output query using TAP/SQL

Full	Name	Mag mag	n_	n_	SpType	Remarks	Bibcode	RAJ2000 "h:m:s"	DEJ2000 "d:m:s"	rc	*Simbad*
1	AG Peg	9.00	V		M1	MWC 379, 1940/41	1942ApJ....95..386M	21 51 01.97	+12 37 32.1	T	Simbad
2	AG Peg	9.00	V		M1/2	1960 Sep 10	1960MitVS.506....1S	21 51 01.97	+12 37 32.1	T	Simbad
3	AG Peg	9.00	V		M3.5		1980MNRAS.192..521A	21 51 01.97	+12 37 32.1	T	Simbad
4	AG Peg	9.00	V		Me		1983MNRAS.203..373F	21 51 01.97	+12 37 32.1	T	Simbad
5	AG Peg	9.00	V		M3III		1987AJ.....93..938K	21 51 01.97	+12 37 32.1	T	Simbad
6	AG Peg	8.70	V		M3IIIe		1988A&A...189...97S	21 51 01.97	+12 37 32.1	T	Simbad
7	AG Peg	9.00	V		M4?e	1992 Jun	1994A&AS..106..413H	21 51 01.97	+12 37 32.1	T	Simbad
8	AG Peg	8.70	V		M3	1989 Aug 15	1999A&AS..137..473M	21 51 01.97	+12 37 32.1	T	Simbad

plot the output query using TAP/SQL

Why being close in altitude matters

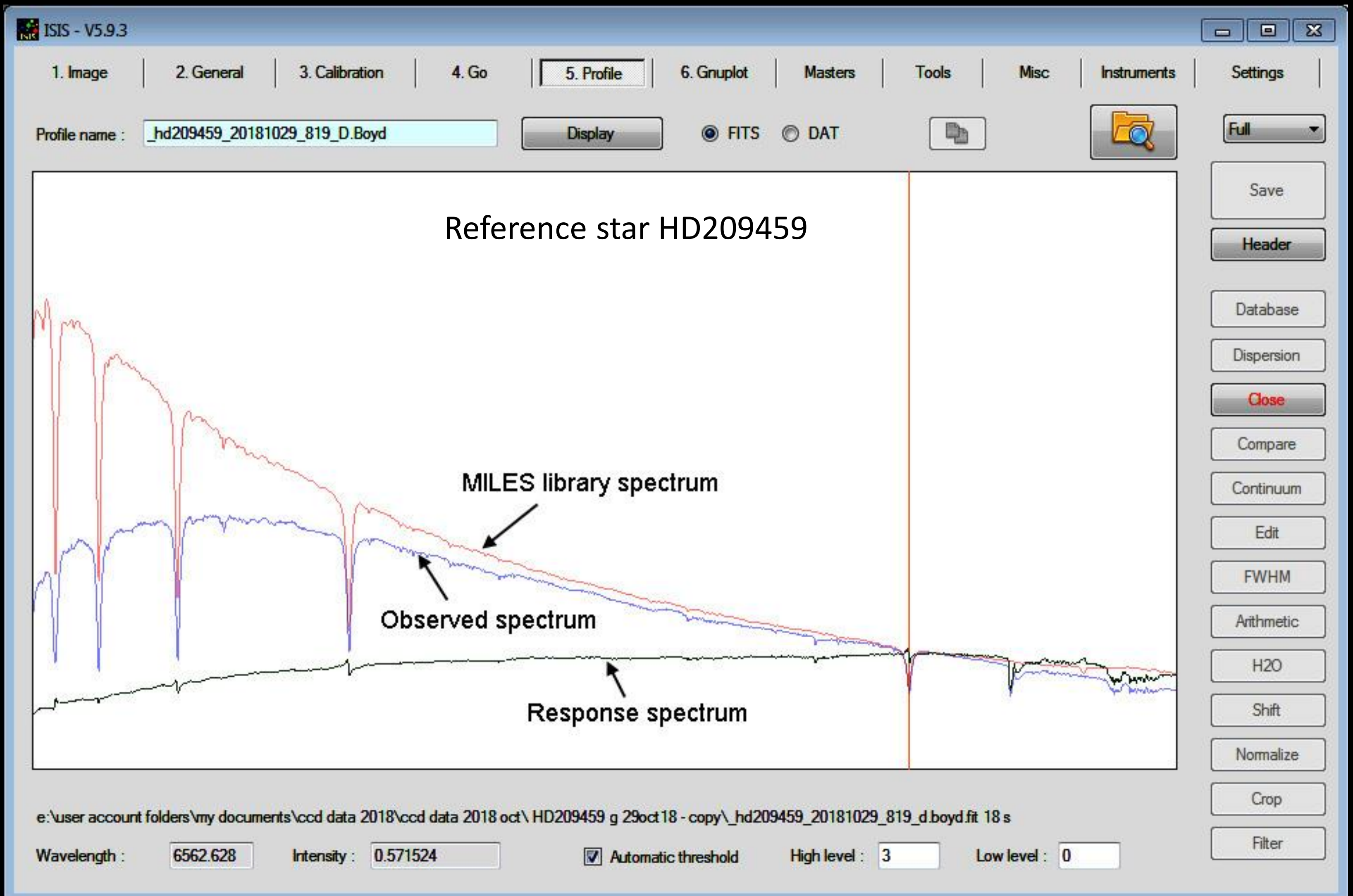
Francois Teyssier's graph shows how altitude separation between reference and target stars varies with altitude for a given required precision when correcting for atmospheric losses.



http://www.astronomie-amateur.fr/Documents%20Spectro/Ref_013.pdf

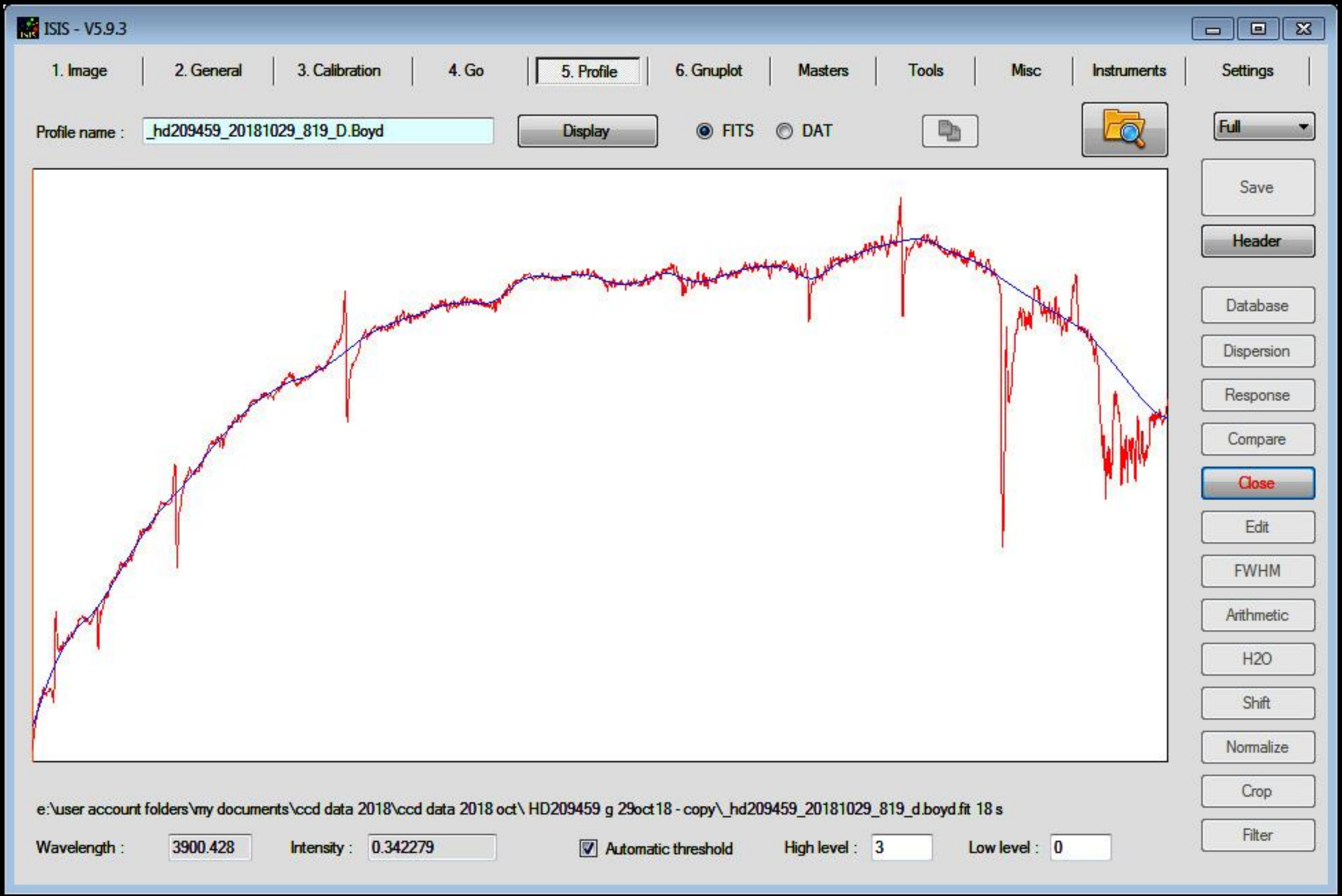
Calculating the response profile (1)

To obtain the response profile, you divide the observed spectrum of the reference star by its exo-atmospheric MILES library spectrum.



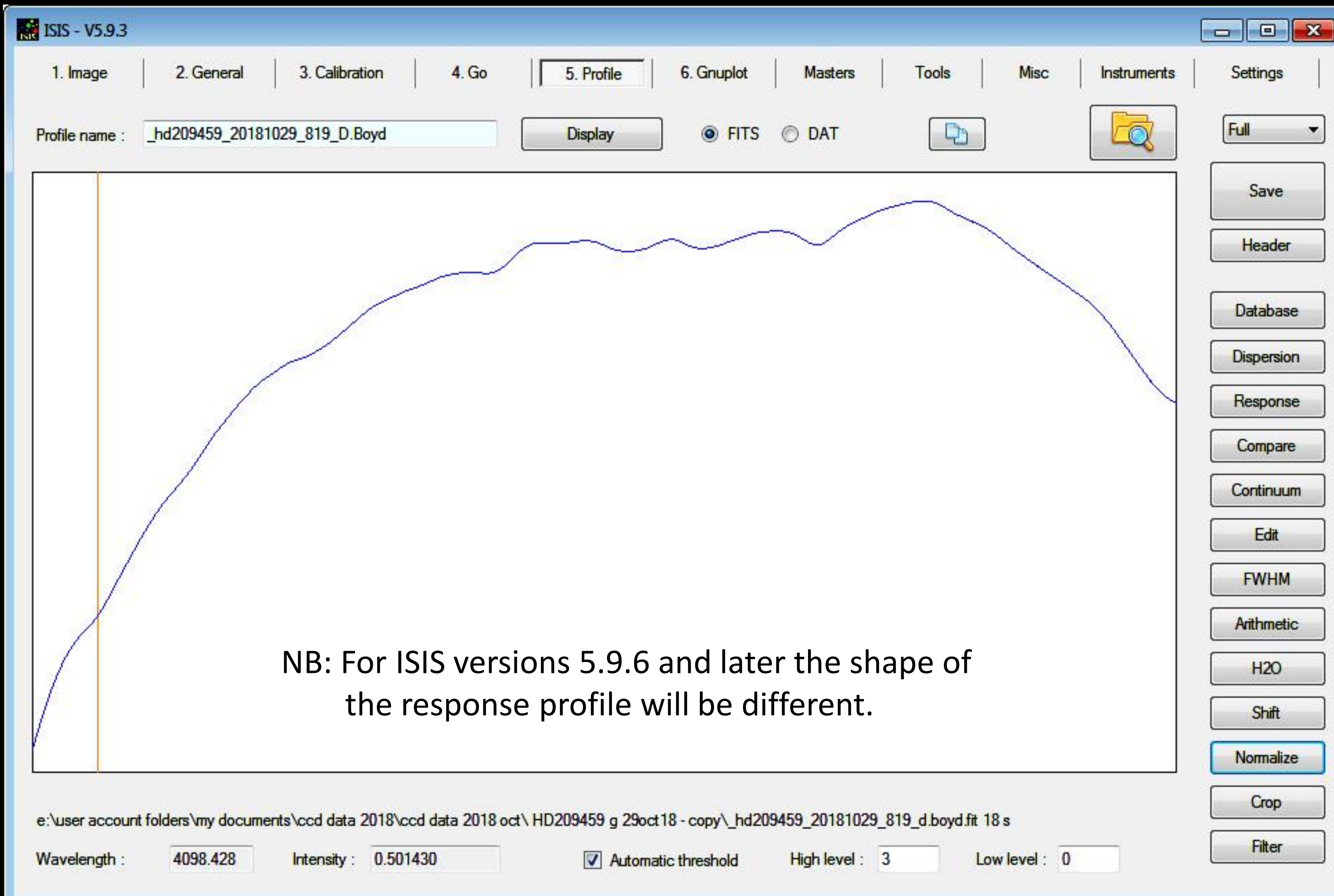
Calculating the response profile (2)

You then smooth the profile to remove vestiges of emission or absorption lines and cut out the large telluric bands at the red end.



Calculating the response profile (3)

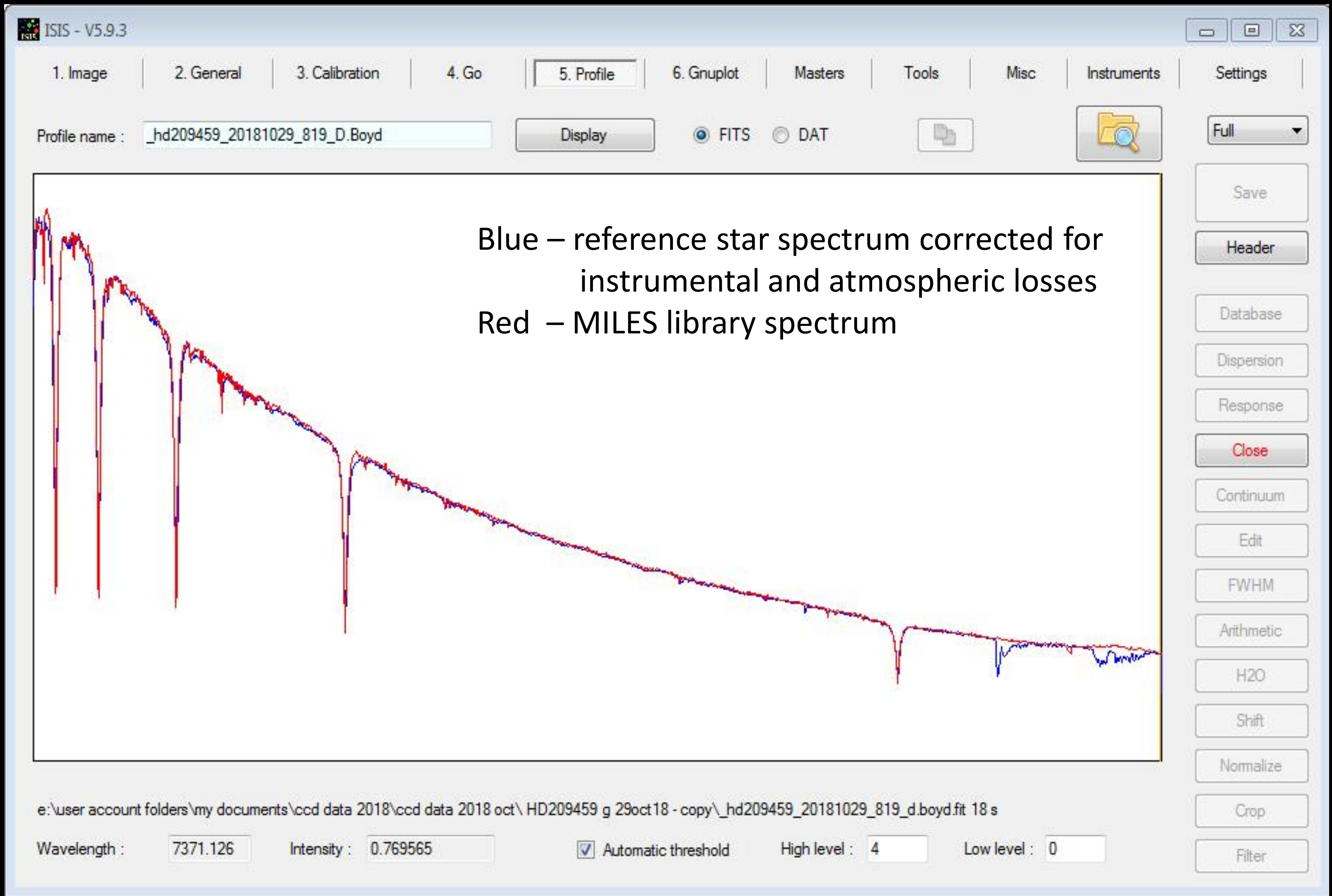
Here is the resulting response profile, ready to use to correct your reference star spectrum for instrumental and atmospheric losses.



NB: For ISIS versions 5.9.6 and later the shape of the response profile will be different.

Applying the response correction

Divide your reference star spectrum by the response profile.
As a sanity check, compare the result with the MILES library spectrum.



Correcting the target star spectrum (1)

We can now take a spectrum of our target star which should be close in altitude (= air mass) to the reference star.

To correct this observed spectrum for instrumental and atmospheric losses, we divide it by the response profile.

True target spectrum = Observed target spectrum / Response profile

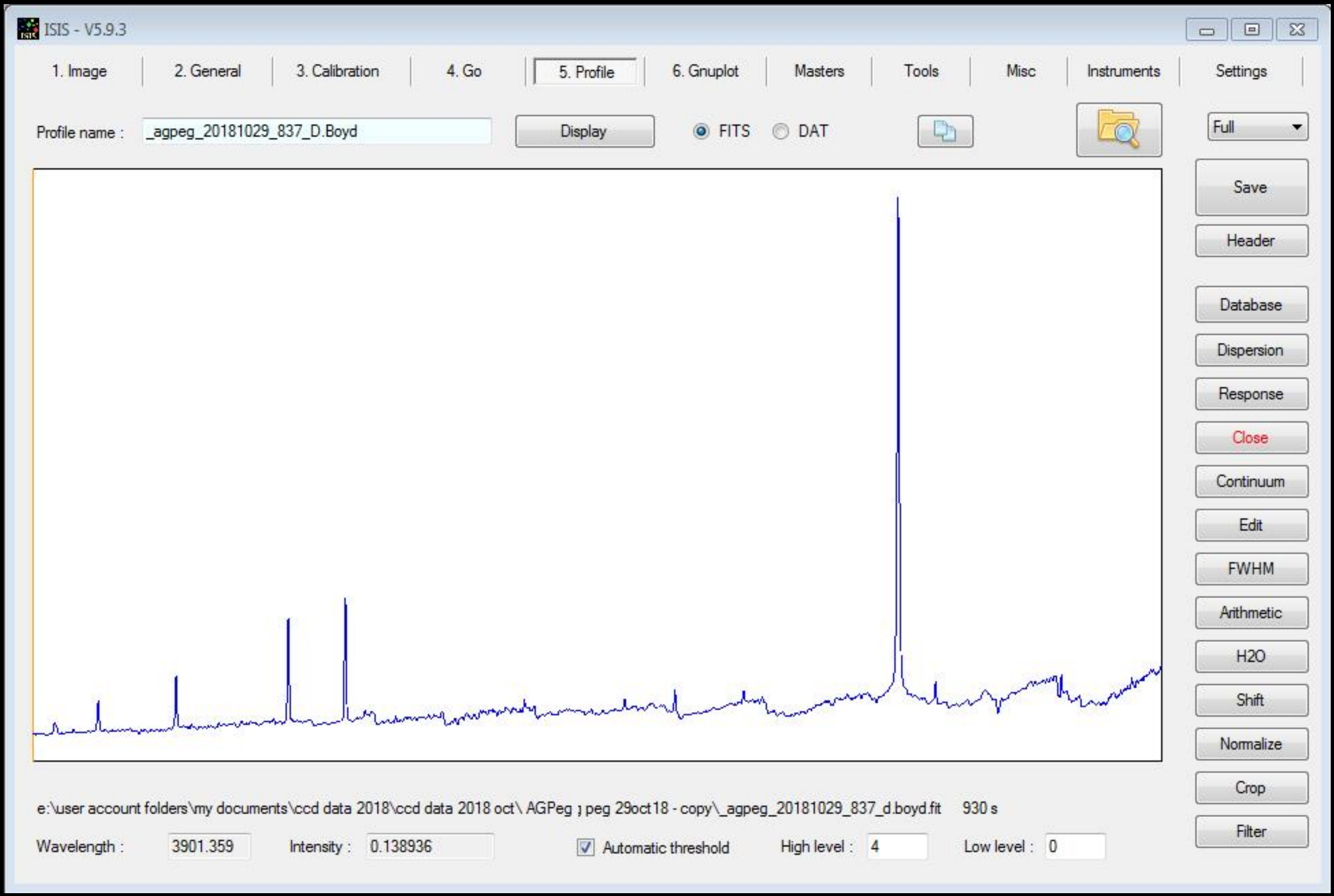
This is now a fully corrected exo-atmospheric spectrum as would be measured by a perfect instrument outside the earth's atmosphere.

It is also a relative flux spectrum as the relative flux level is consistent across the spectrum but its absolute level is not defined.

This is normally the minimal level of processing required by amateur spectroscopic databases.

Correcting the target star spectrum (2)

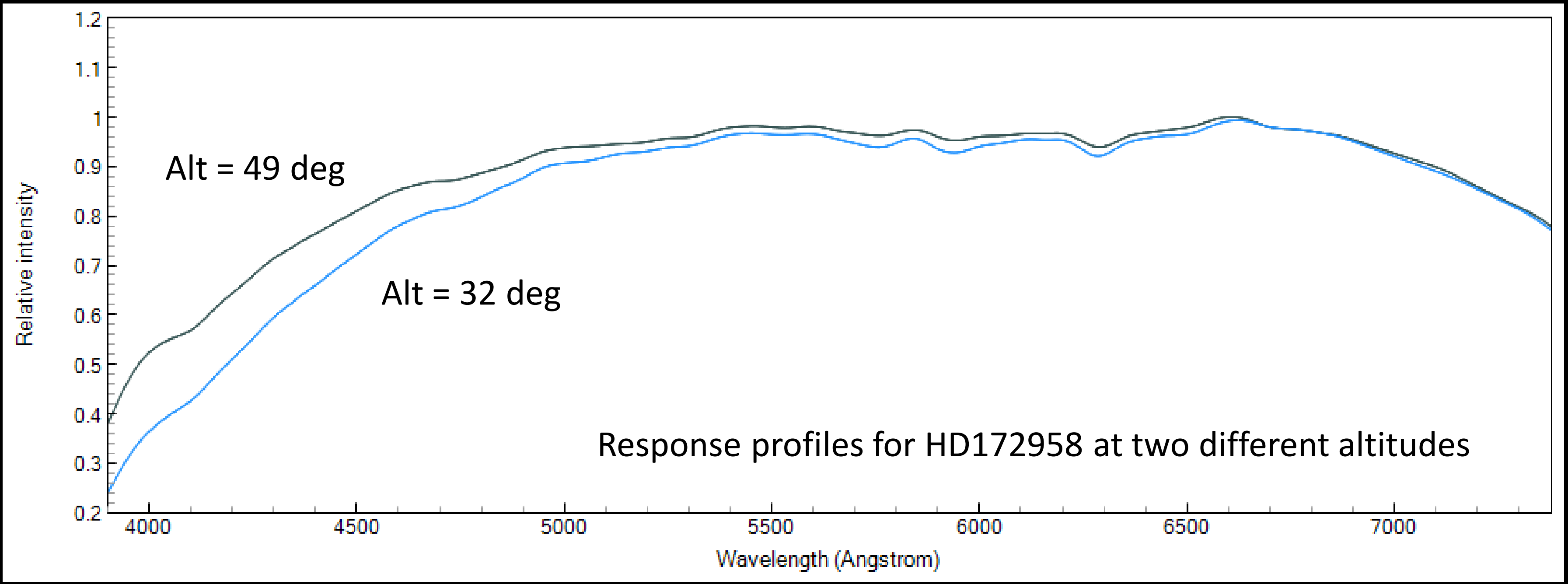
Here is the exo-atmospheric relative flux spectrum of AG Peg.



Beware big changes in altitude

If the target star altitude has changed a lot during your observations, consider taking a second set of reference star spectra after the target star observations at the same altitude as the target star has reached at that time.

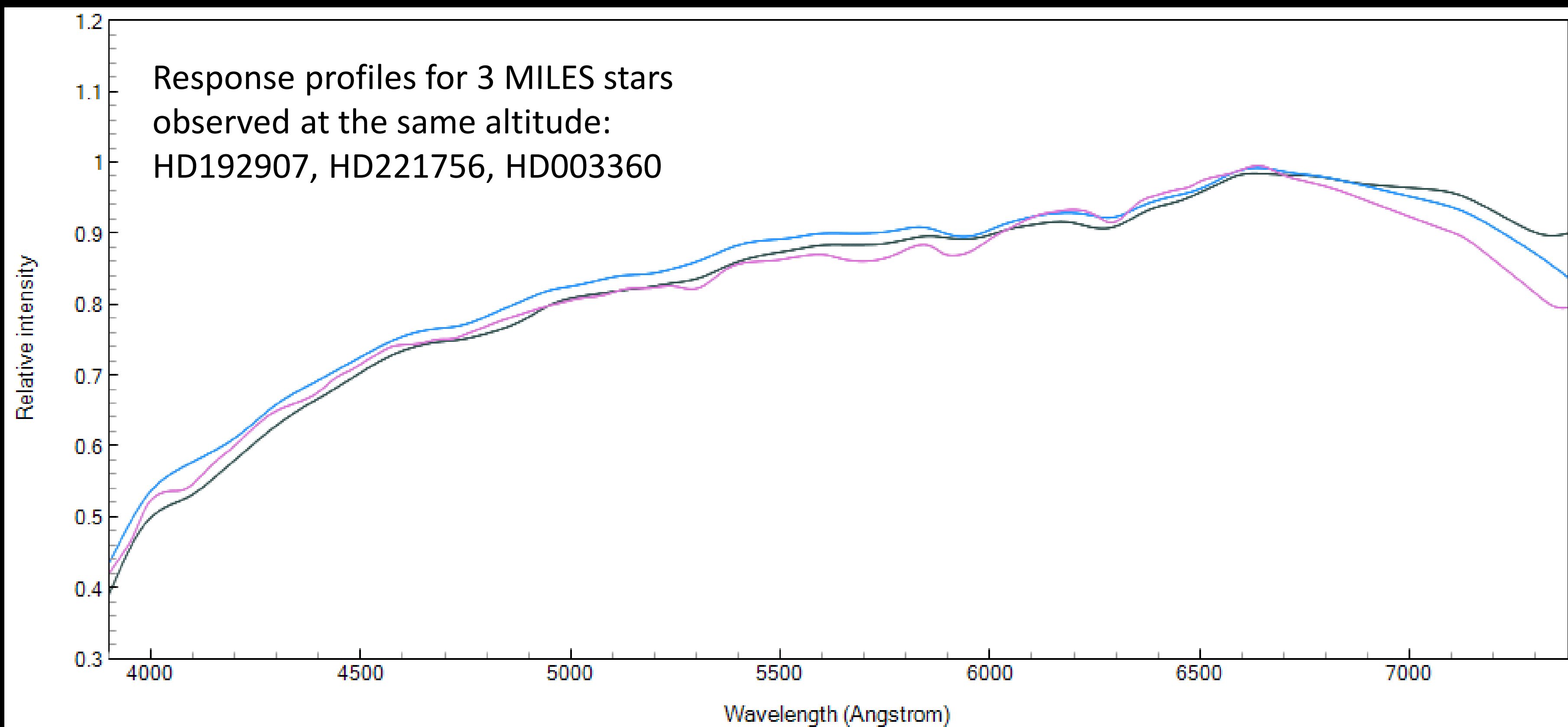
Using either the same reference star or a different one you can calculate two response profiles and use an average of them to correct the target star spectra.



Response profiles for HD172958 at two different altitudes

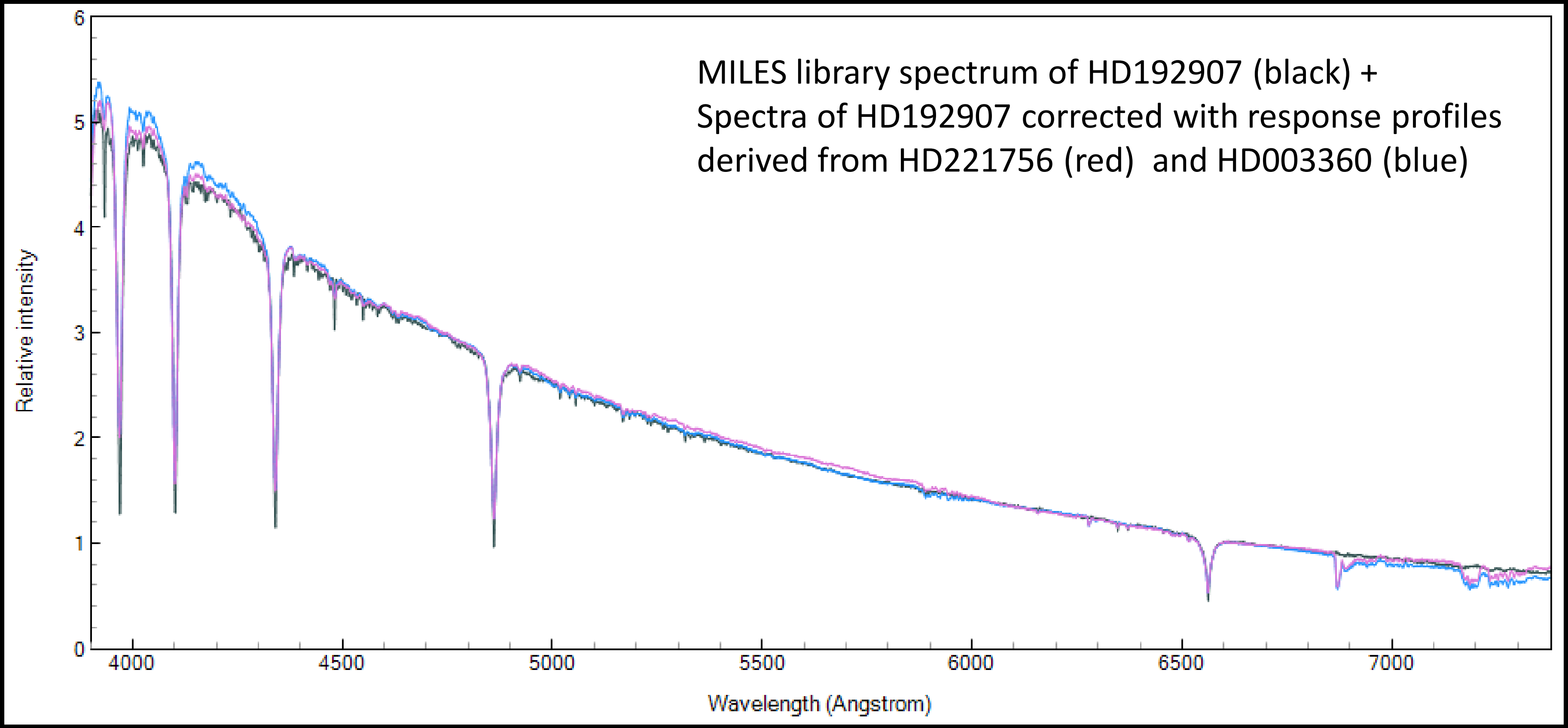
Testing the consistency of response profiles (1)

You can test the consistency of your procedure for measuring the response profile by taking spectra of (say) three MILES stars at very similar altitudes on the same night and comparing the three response profiles.



Testing the consistency of response profiles (2)

You can then use the other two reference profiles to correct the spectrum of one of the stars and compare with its MILES library spectrum.

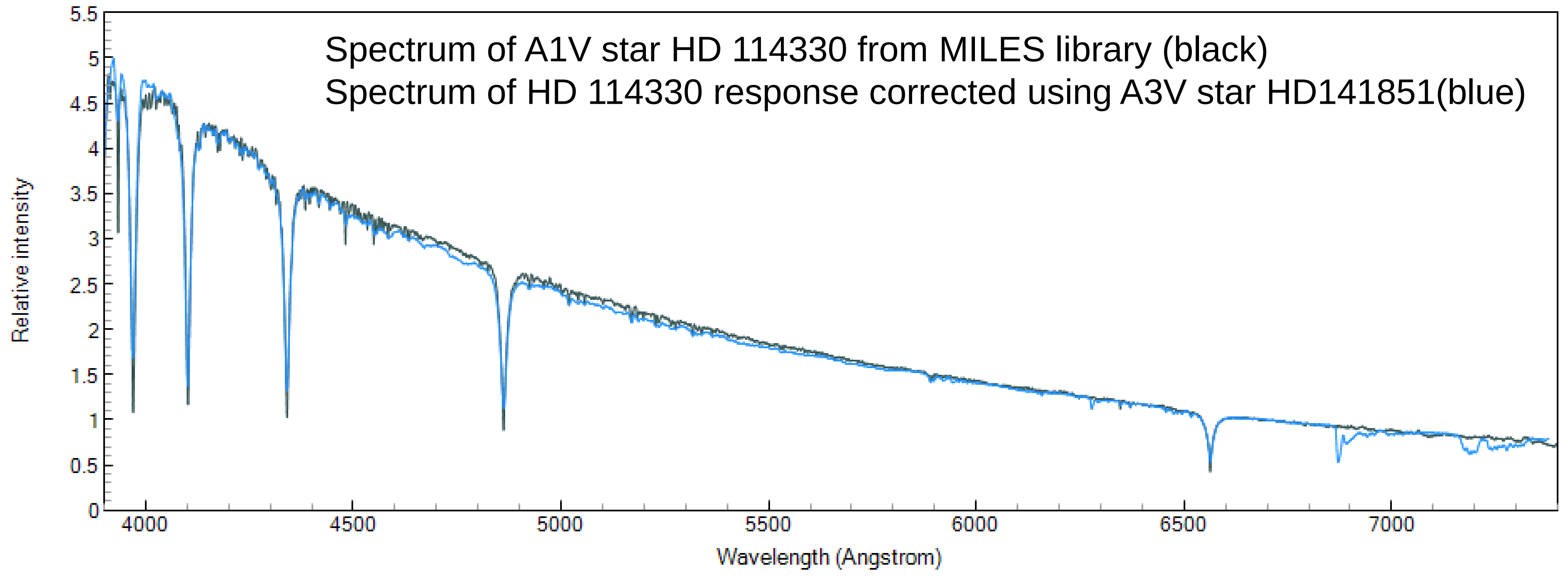


Reference stars and parallactic angle

Does using a close reference star mitigate the parallactic angle requirement?

Worst case scenario – spectra of 2 MILES stars recorded both at airmass = 2 with the slit horizontal.

A3V star HD141851 used as reference to response correct A1V star HD114330.



Description of professional spectral reduction

This paper describes the reduction of spectroscopy at the Keck Observatory.

They face many of the same problems amateurs do but have less control over the state of the equipment!

D. A. Perley, Fully-Automated Reduction of Longslit Spectroscopy with the Low Resolution Imaging Spectrometer at Keck Observatory
https://arxiv.org/abs/1903.07629v3

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Rectification and Normalisation (1)

These terms are often confused and misunderstood.

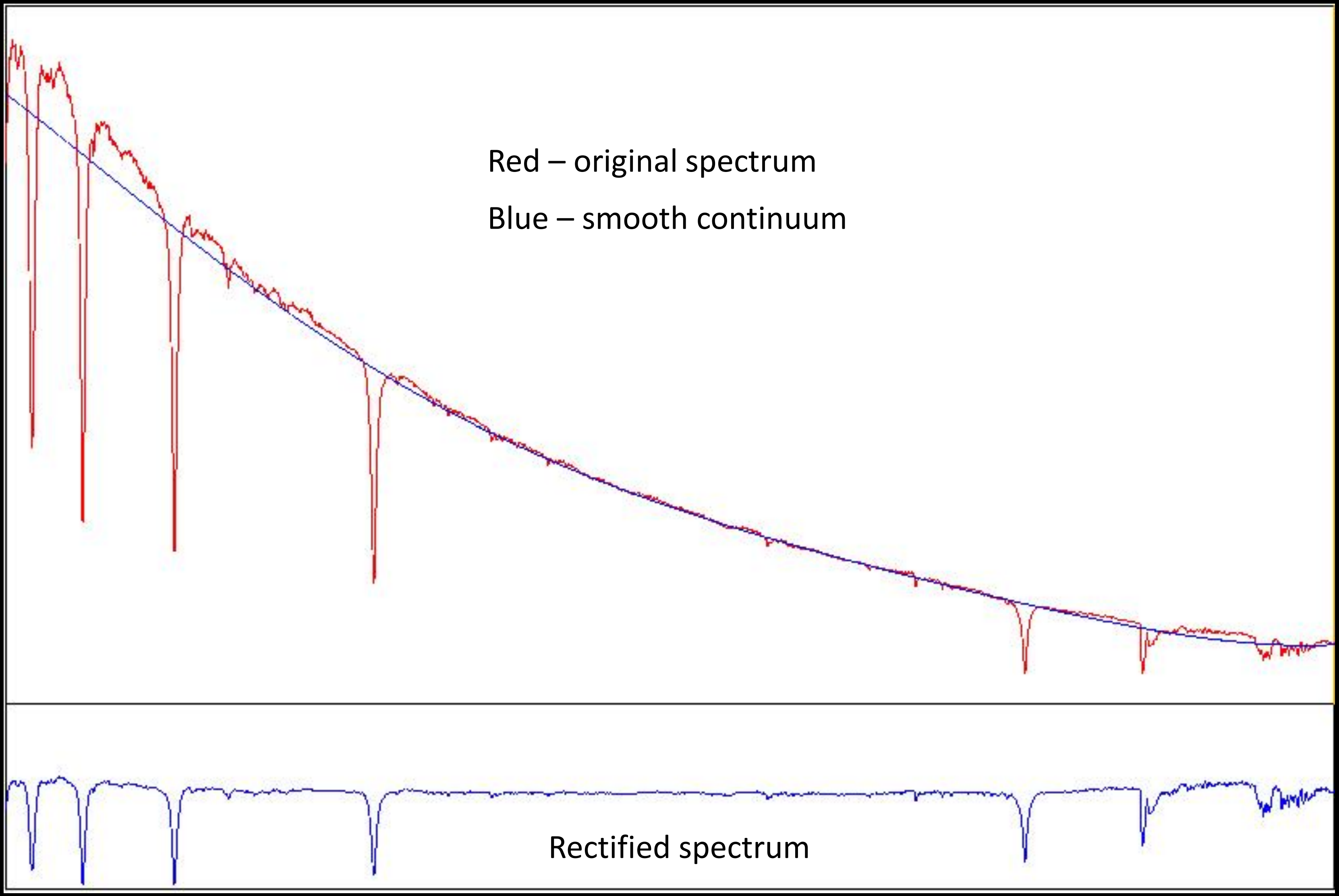
Rectification involves fitting a smooth continuum profile to a spectrum and dividing the spectrum by that smooth continuum.

The result is a spectrum whose profile is everywhere close to unity.

Many spectra in Gray & Corbally are rectified as this makes it easier to classify them using absorption line flux ratios.

R. O. Gray & C. J. Corbally, *Stellar Spectral Classification*, Princeton University Press (2009)

Example of rectification



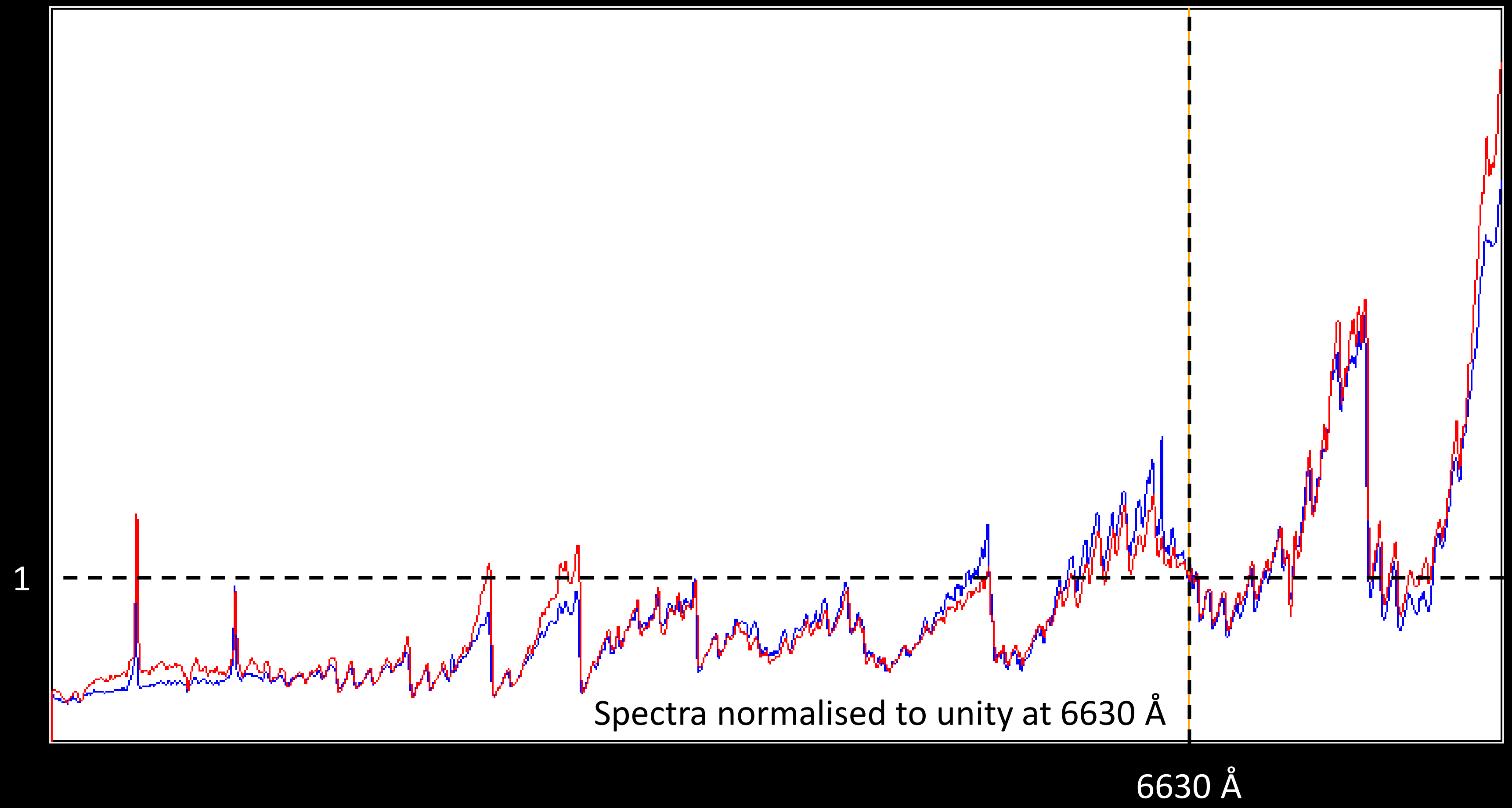
Rectification and Normalisation (2)

Normalisation is aligning one or more spectra such that the flux at a particular wavelength is set to unity in all the spectra.

In late type stars with complex molecular absorption bands it is difficult to correctly identify the smooth continuum profile so they cannot be accurately rectified.

They are usually shown as normalised thus retaining their original spectral profile.

Example of normalisation



The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum
- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux
- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

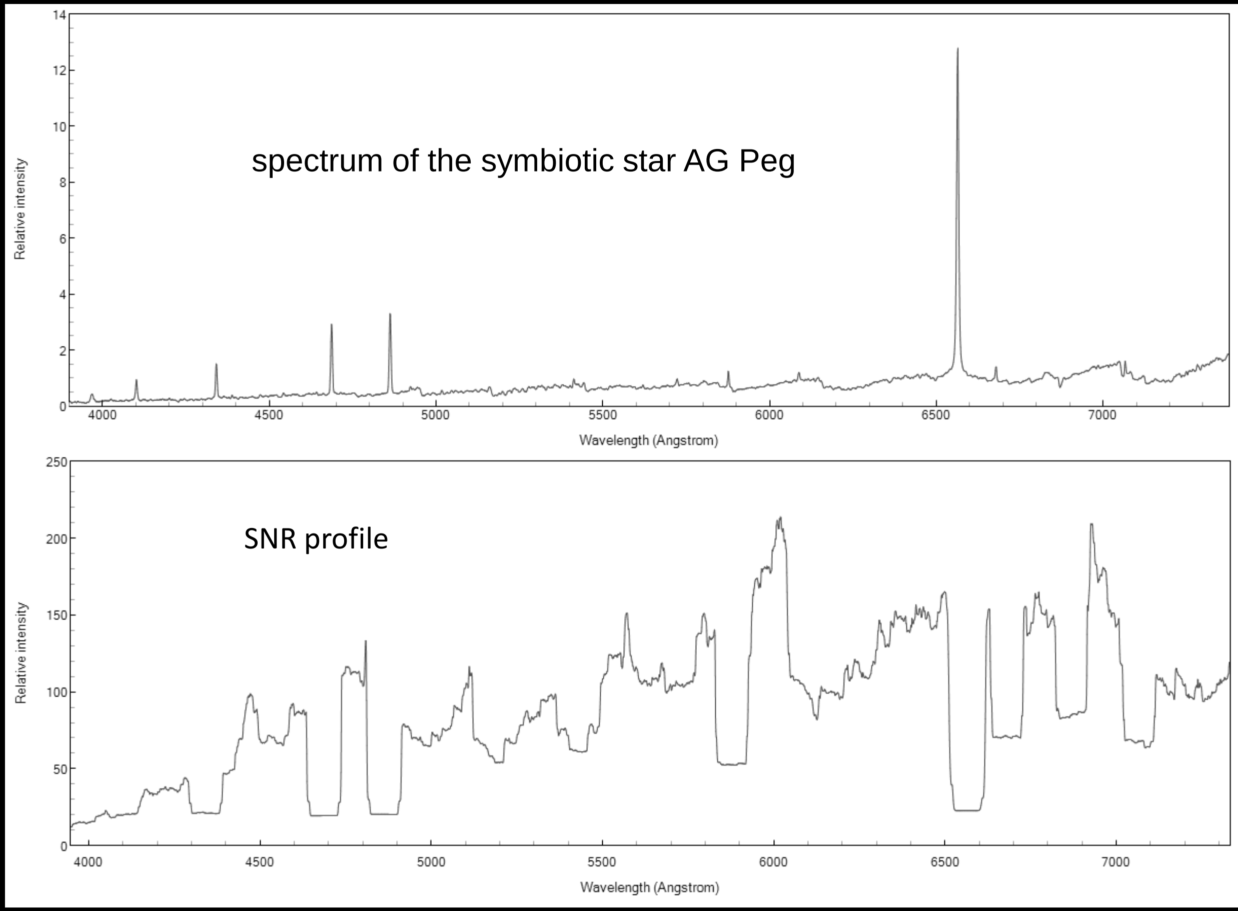
3) Correcting for interstellar extinction and reddening
- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Estimating signal to noise ratio (SNR) (1)

Some analysis packages include techniques for estimating the SNR in a spectrum.

The general principle behind these is to look at random noise fluctuations in regions of the spectrum which have a smooth continuum with no emission or absorption lines.

PlotSpectra software by Tim Lester has a facility for calculating the SNR of a spectrum by comparing two subsets of the spectrum.



Estimating signal to noise ratio (SNR) (2)

There is an algorithm called DER_SNR which estimates a global SNR for a spectrum.

F. Stoehr et al., *DER SNR: A Simple & General Spectroscopic Signal-to-Noise Measurement Algorithm*, ASP Conference Series, Vol. XXX, 2008
http://www.stecf.org/software/ASTROsoft/DER_SNR/

This was developed by a working group of professional astronomers to meet the need for a common SNR estimator which could be applied to spectra from a wide variety of databases and instruments.

The algorithm is simple:

signal = median(flux(i))
noise = 1.482602 / sqrt(6.0) * median(abs(2 * flux(i) - flux(i-2) - flux(i+2)))
DER_SNR = signal / noise

where the median calculations are done over all non-zero pixels of the spectrum.

It has the appeal that it is easily implemented in a spreadsheet.
IDL and Python versions are also available.

Estimating signal to noise ratio (SNR) (3)

Christian Buil's ISIS package includes three methods which he describes in this ARAS Forum posting:
http://www.spectro-aras.com/forum/viewtopic.php?f=8&t=1564&p=7468#p7177

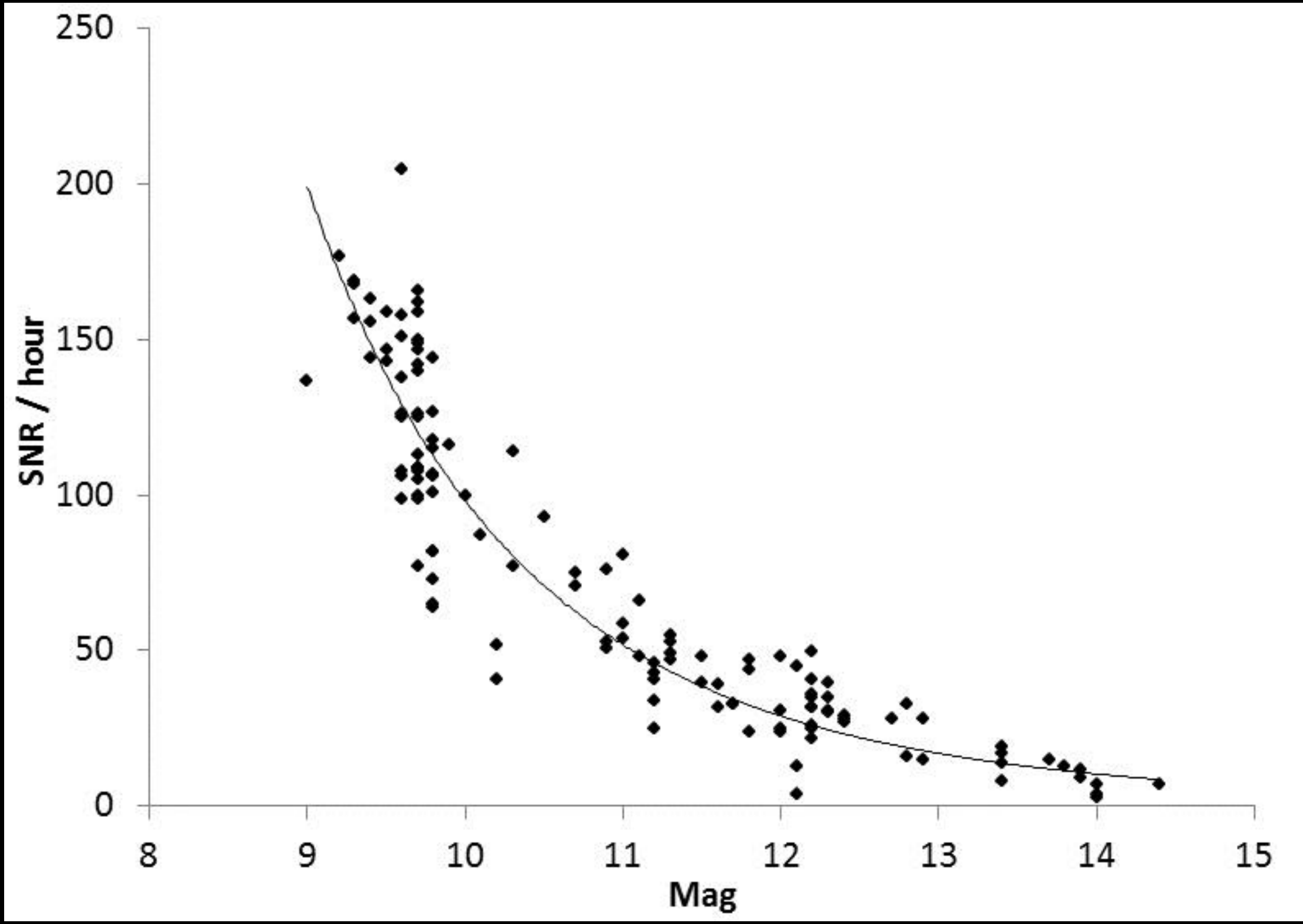
The third of these is an implementation of DER_SNR

PlotSpectra, ISIS and the DER_SNR algorithm all give global values close to 100 for the SNR of the AG Peg spectrum shown earlier.

- These methods all give SNR <u>estimates</u> and should not be taken as definitive measurements of the SNR in a spectrum.
- However they are as good as we are likely to need in assessing the relative quality of any given spectrum.
- Bear in mind these are statistical error estimates and do not include any systematic effects which may be difficult to assess.

Estimating signal to noise ratio (SNR) (4)

This plot shows the SNR per hour of exposure vs V mag for 128 spectra of symbiotic stars recorded with a LISA spectroscope.



The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Measuring equivalent width of spectral lines (1)

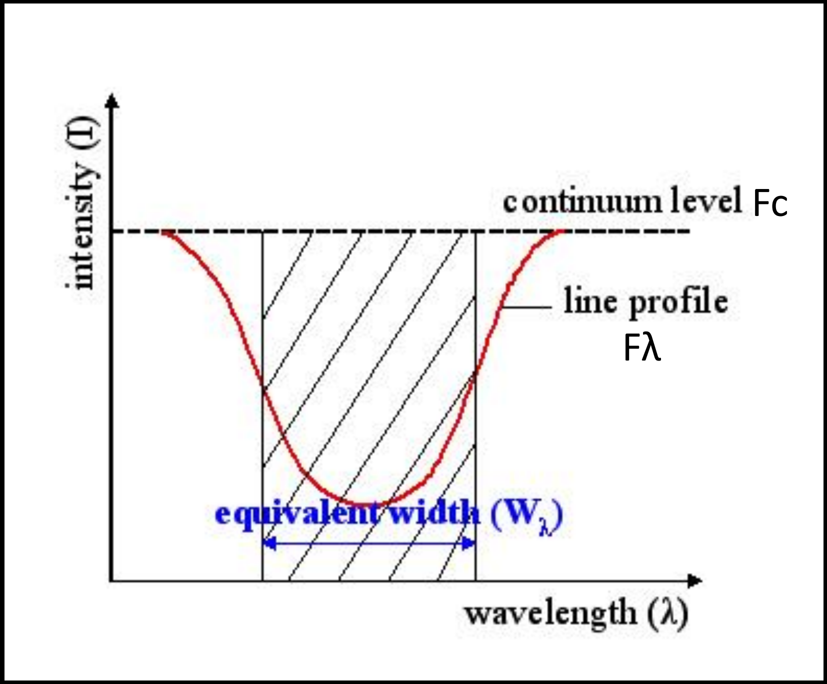
The equivalent width (EW) of absorption or emission lines in a relative flux spectrum is the integrated flux in the line below or above the local continuum and is measured in Å.

First we need to rectify the spectrum in the vicinity of the line by dividing the spectrum by the continuum profile across the line.

We then sum the area between the line profile and the continuum level to get the EW of the line in Å.

$$EW = \Sigma\, [(Fc - F\lambda) / Fc]\, d\lambda$$

where Fc is the continuum flux, Fλ the flux at wavelength λ and dλ the wavelength bin size.

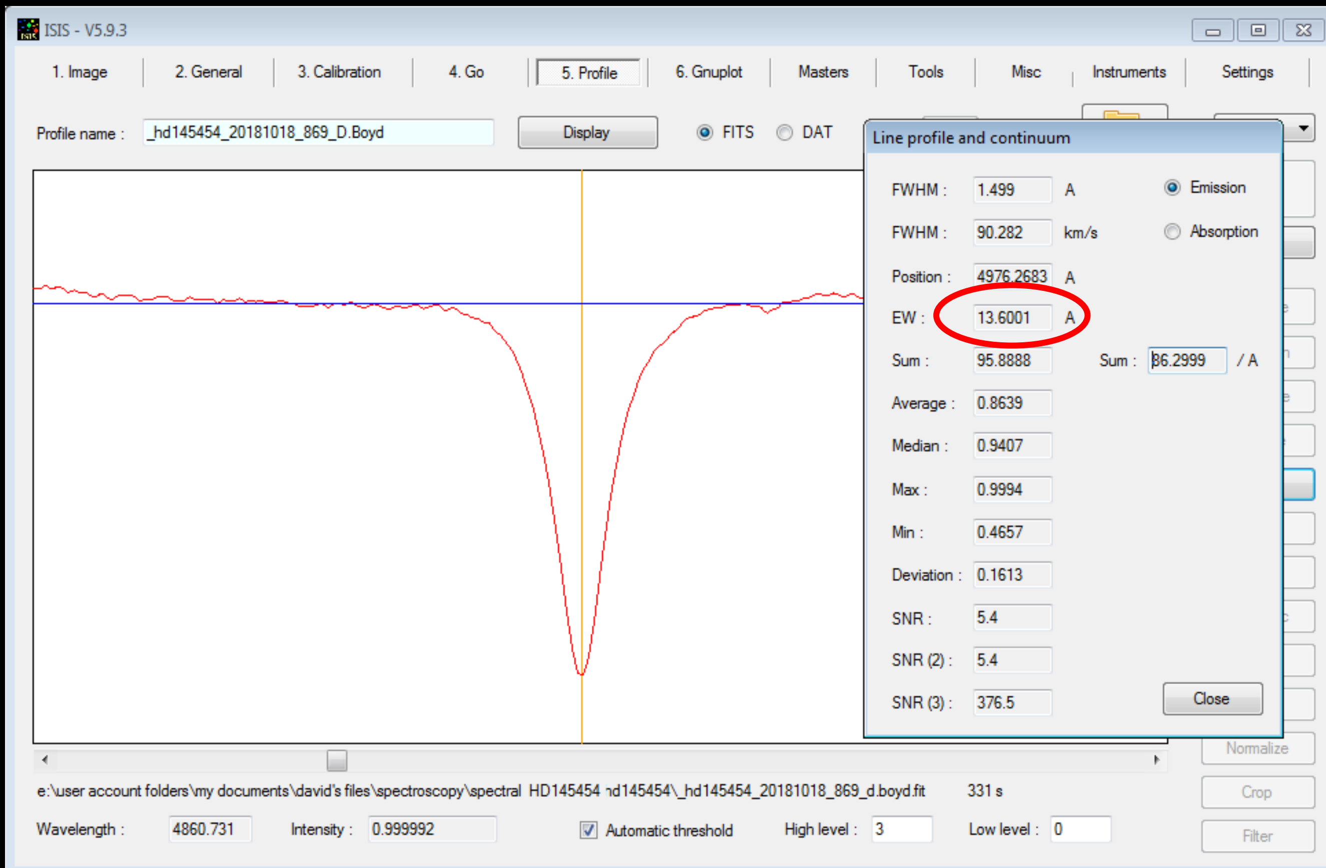


Measuring equivalent width of spectral lines (2)

By convention EW is negative for emission lines and positive for absorption lines.

This is a measurement using ISIS of the EW of the Hβ absorption line in a relative flux spectrum of HD145454, an A0V type star.

The continuum has been rectified to unity and the EW is 13.60 Å.



Take care identifying spectral lines

Beware of looking up spectral lines by wavelength in catalogues of spectral lines.

You sometimes see the result of that in online fora where no physics knowledge has been used and lines are mis-identified.

First familiarise yourself with previous published work on that star or others of the same spectral type to see what line identifications have been established by others.

If you can find no previous identifications, try to understand the physical processes and local stellar conditions which will be influencing emissions or absorptions in the star's spectrum.

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Do we need to flux calibrate our spectrum?

We have seen how to produce a relative flux spectrum such as would be observed by a perfect instrument observing from outside the atmosphere.

This means the relative value of the flux, or intensity, of the light is represented consistently across the spectrum.

We can follow qualitative changes in the flux profile over time.

If this is sufficient for our purpose, there is no need to flux calibrate the spectrum.

However this leaves some of the scientific potential of the spectrum untapped.

What do we mean by absolute flux calibration?

An absolute flux spectrum of a star provides a quantitative measure of its spectral energy distribution (SED) in physical units such as erg/cm^2/s/Å.

It is a direct measurement of the amount of energy received from the star as a function of wavelength.

The process of measuring absolute flux is often called spectrophotometry.

It is normally defined with respect to a set of spectrophotometric standard stars.

A spectrum calibrated in absolute flux enables us to do more useful science.

How absolute flux is measured (1)

The process of measuring absolute flux has a long history.

Initial measurements of absolute flux were based on calibrating ground-based observations of Vega with laboratory flux standards.

This necessitated making accurate measurements of instrumental losses and atmospheric extinction as functions of wavelength and time (as we discussed earlier).

Establishing reliable stellar absolute flux based on laboratory flux standards proved to be difficult.

Later rockets were used to make observations outside the atmosphere.

How absolute flux is measured (2)

This led to the use of pure hydrogen DA white dwarf model atmospheres as flux standards
– with only one element these are relatively simple to calculate.

The photon emission spectrum of DA white dwarf stars is a function of two parameters which can be measured with ground-based spectroscopy – effective temperature T_{eff} and surface gravity g.

Calibration of these models is tied to measurements of the absolute monochromatic flux of Vega at 5556 Å and also to the broadband photometric standards established by Landolt.

How absolute flux is measured (3)

Three pure hydrogen white dwarfs with absolute flux precision better than 1% have been established as primary flux standards from which other secondary standards have been calibrated.

The most precise existing network of spectrophotometric standard stars for absolute flux calibration are the 93 stars in the CALSPEC archive.
http://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/calspec

These were measured by HST (thus avoiding atmospheric extinction) and calibrated using the three white dwarf primary standards.

The majority have V magnitudes in the range 6 – 13.

The precision in absolute flux of these stars in the visual part of the spectrum is stated as better than 2%.

How absolute flux is measured (4)

Most of the CALSPEC standards are relatively bright and saturate large aperture instruments so a network of 19 faint DA white dwarfs (mags 17-20) has recently been established using HST as new spectrophotometric standards.

Narayan et al., *Sub-percent Photometry: Faint DA White Dwarf Spectrophotometric Standards for Astrophysical Observatories* (2018)
https://arxiv.org/pdf/1811.12534.pdf
Calamida et al., *Photometry and spectroscopy of faint candidate spectrophotometric standard DA white dwarfs* (2018)
https://arxiv.org/pdf/1812.00034.pdf

These have precision better than 1% to match the quality of data expected from the next generation of wide field surveys (ZTF, LSST).

Where necessary, these model-based white dwarf spectra have been reddened to account for interstellar extinction to the star.

How absolute flux is measured (5)

There is a version of the Pickles library of 131 synthesised spectra for most spectral types and luminosity classes which has reputedly been flux calibrated by normalizing fluxes in the Pickles V band to zero magnitude in the VEGAMAG system.

http://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/pickles-atlas

The uncertainty in determining the absolute flux of a target star should include the uncertainty in the flux standard(s) used together with uncertainties in measurements of the standard and target stars plus any systematic effects.

Together these factors set a limit on achievable accuracy for the absolute flux calibration process.

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

How to calibrate spectra in absolute flux

The principle is simple (!)

Using a stable instrument with linear response we measure the relative flux of the target R_T and the relative flux of a spectrophotometric standard star R_S whose absolute flux is A_S.

The absolute flux of the target A_T is then given by:

$$A_T = R_T \times A_S / R_S$$

This assumes the same conditions throughout (slit size, photometric sky, etc) and all measured fluxes are exo-atmospheric.

For a good review of the issues involved in absolute flux calibration:
R. C. Bohlin et al., *Techniques and Review of Absolute Flux Calibration from the Ultraviolet to the Mid-Infrared*, PASP, 126, 711 (2014)
https://iopscience.iop.org/article/10.1086/677655/pdf

Practical absolute flux calibration

For us amateurs, there are basically two approaches available for absolute flux calibration:

a) Record the spectrum of a star, such as a MILES reference star, whose absolute flux at a specific wavelength can be estimated from its known magnitude, and derive from that a flux calibration which can then be applied to the target star.

   This method is described by Christian Buil on his website:

   http://www.astrosurf.com/buil/calibration2/absolute_calibration_en.htm

b) Measure the V magnitude of the target star concurrently with the spectrum and use that to derive a flux calibration for the target.

   This is the method I use and is described here:

   http://www.spectro-aras.com/forum/viewtopic.php?f=8&t=897#p4044

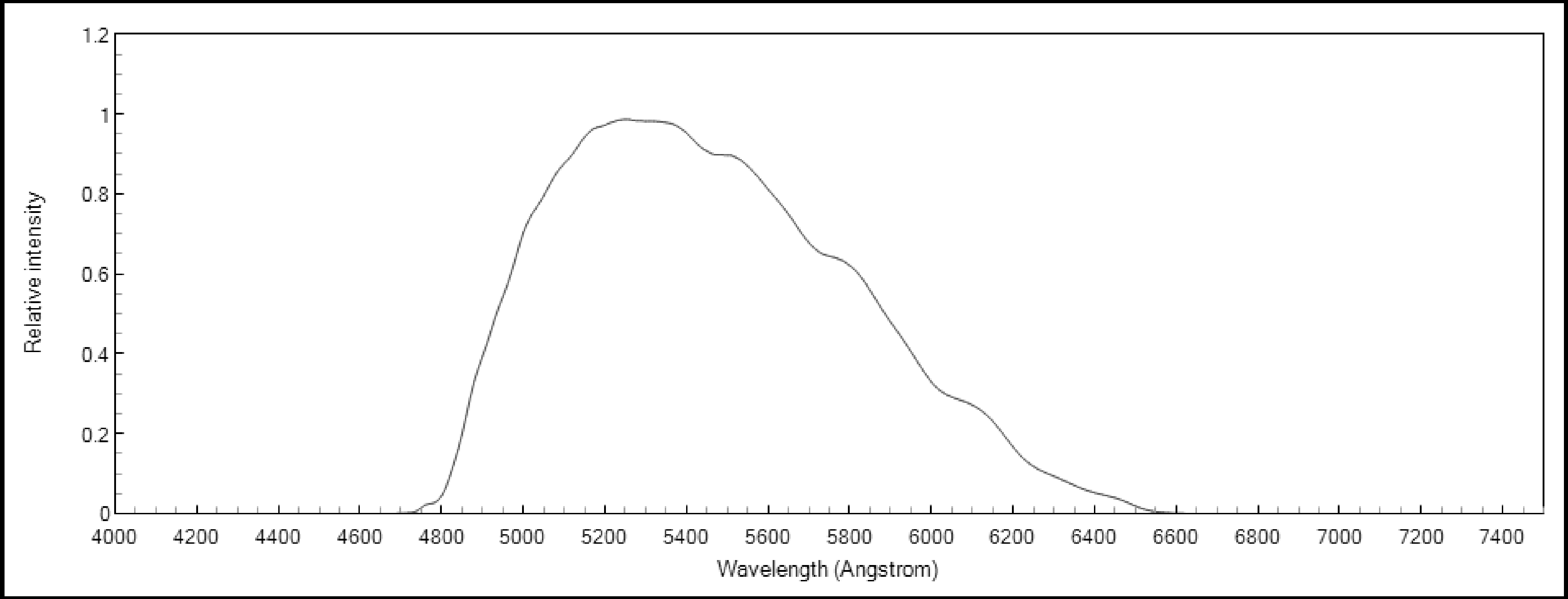
   It is follows work by Martin Dubs, Francois Teyssier, Robin Leadbeater & others.

Absolute flux calibration using a V magnitude

First you need to know V(λ) the spectral transmission profile of your V filter.

You should be able to get this from the filter manufacturer.

This is the transmission profile V(λ) of my Astrodon V filter.



Next you need to find the spectroscopic zero point of your V filter

Suppose $A_S(\lambda)$ is the absolute flux spectrum of a spectrophotometric standard star, such as a star from the CALSPEC library.

The absolute V-band flux of this standard star transmitted by the V filter is then

$$\int V(\lambda)\, A_S(\lambda)\, d\lambda$$

The measured V magnitude m_S of the standard star is given by

$$m_S = -2.5 \log_{10} \left[\int V(\lambda)\, A_S(\lambda)\, d\lambda \right] - ZP$$

where ZP is the spectroscopic zero point magnitude of your V filter.

$$ZP = -m_S - 2.5 \log_{10} \left[\int V(\lambda)\, A_S(\lambda)\, d\lambda \right]$$

We can calculate this zero point for each of the CALSPEC standard stars as follows . . .

ID	Sp type	V mag	V-band flux	Zero point
BD+17_4708	sfF8	9.47	5.6767E-10	13.645
BD+25_4655	B0	9.68	4.7670E-10	13.624
BD+28_4211	Op	10.51	2.2346E-10	13.617
BD+33_2642	B2IV	10.83	1.6718E-10	13.612
BD+75_325	O5p	9.55	5.4967E-10	13.600
FEIGE110	D0p	11.83	6.5565E-11	13.628
G93-48	DA3	12.74	2.8068E-11	13.639
1732526	A4V	12.53	3.4390E-11	13.629
1740346	A6V	12.48	3.5439E-11	13.646
1743045	A8III	13.52	1.3698E-11	13.638
1802271	A2V	11.98	5.6297E-11	13.644
1805292	A4V	12.28	4.2837E-11	13.640
1812095	A5V	11.74	7.0920E-11	13.633
HD209458	G0V	7.65	3.0378E-09	13.644
HD93521	O9Vp	6.99	5.6932E-09	13.622
HZ44	sdO	11.67	7.7100E-11	13.612
Vega	A0V	0.03	3.4580E-06	13.623
			Mean	13.629
			Std dev	0.014

V-band flux in $erg/cm^2/s/Å$
$= \int V(\lambda)\, A_S(\lambda)\, d\lambda$

Zero point in magnitudes
$= -\text{V mag} - 2.5 \log_{10}(\text{flux})$

← Mean V filter spectroscopic zero point ZP

Suppose $A_T(\lambda)$ is the absolute flux spectrum from our target star (this is what we want to know).

The measured V magnitude of the target star is given by

$$m_T = -2.5 \log_{10} [\int V(\lambda) A_T(\lambda) d\lambda] - ZP$$

The absolute V-band flux from the target star is

$$A_V = \int V(\lambda) A_T(\lambda) d\lambda = 10^{[-0.4 * (m_T + ZP)]}$$

If $R_T(\lambda)$ is the relative flux spectrum of our target star (what we measure) then its relative V-band flux is

$$R_V = \int V(\lambda) R_T(\lambda) d\lambda$$

We can then find the absolute flux spectrum $A_T(\lambda)$ by scaling the relative flux density $R_T(\lambda)$ by A_V / R_V

Worked example: BD+25 4655

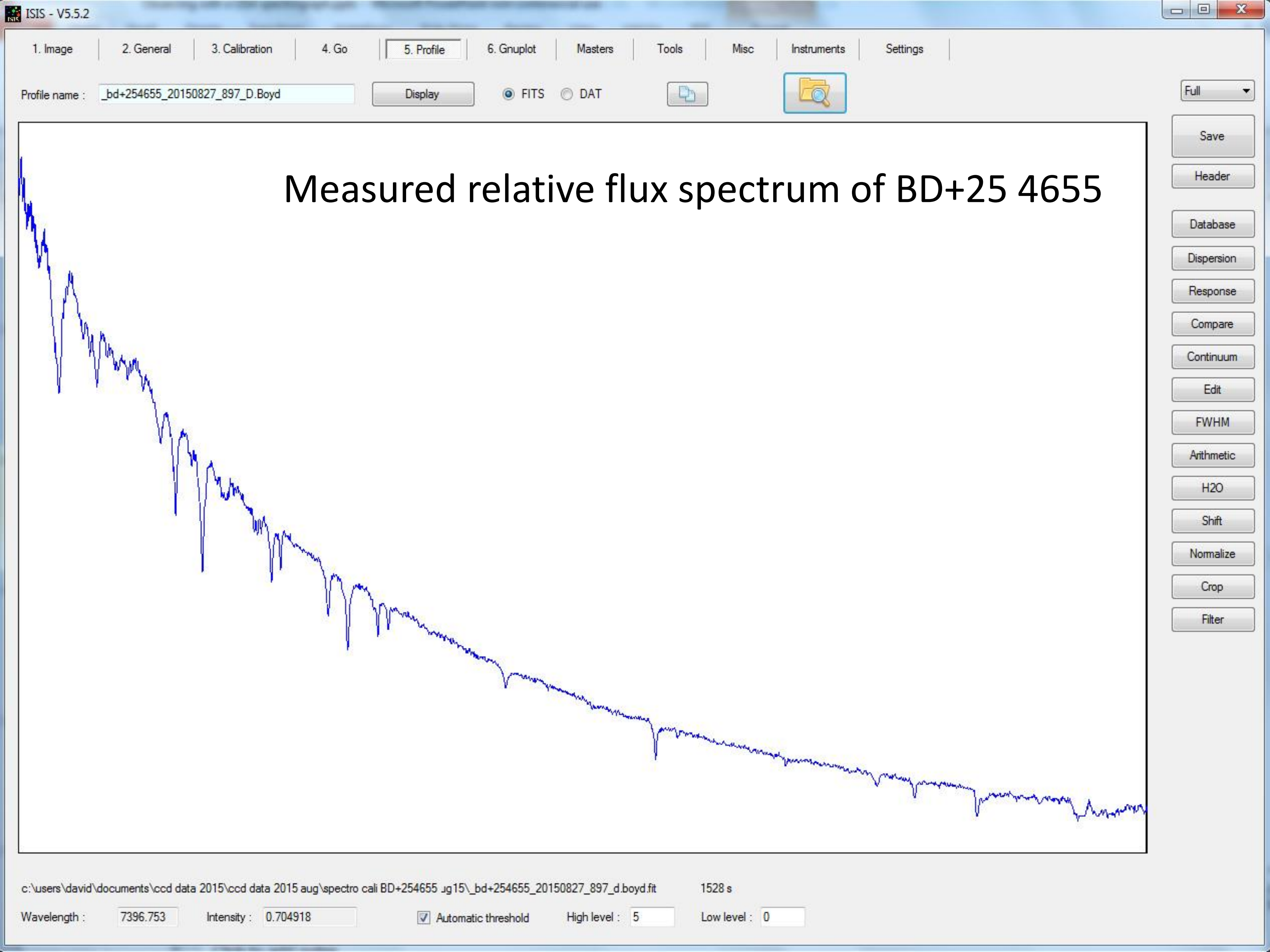
- We know $m_T = 9.68$

- So we know the absolute V-band flux transmitted by the V filter is
  $A_V = 10^{[-0.4*(9.68 + 13.63)]} = 4.7424 \times 10^{-10}$ erg/cm²/s/Å

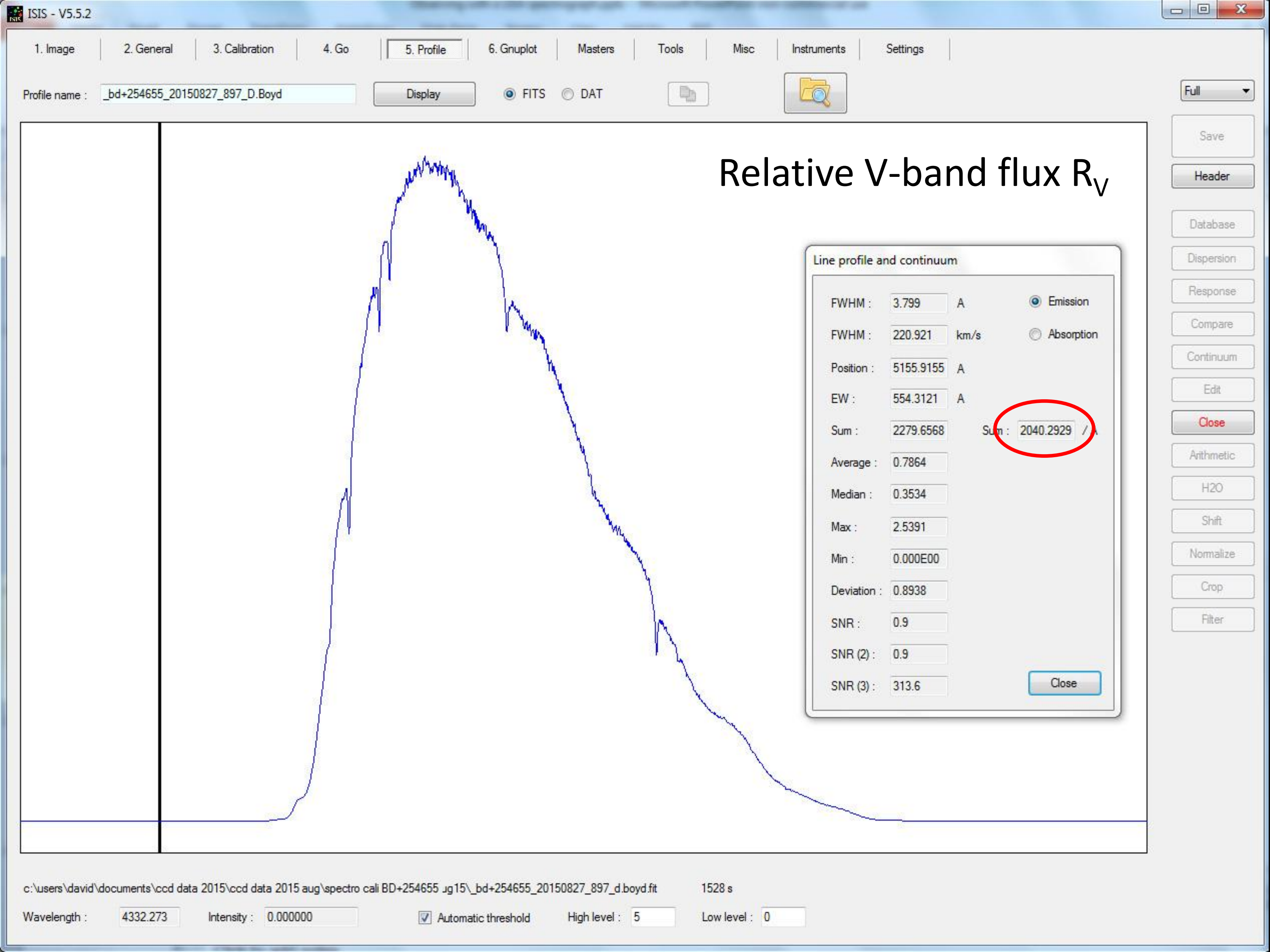
- Measure a relative flux spectrum of BD+25 4655 in ADU, multiply it by the V filter profile and measure the relative V-band flux
  $R_V = \int V(\lambda)\, R_T(\lambda)\, d\lambda = 2040.2929$ ADU

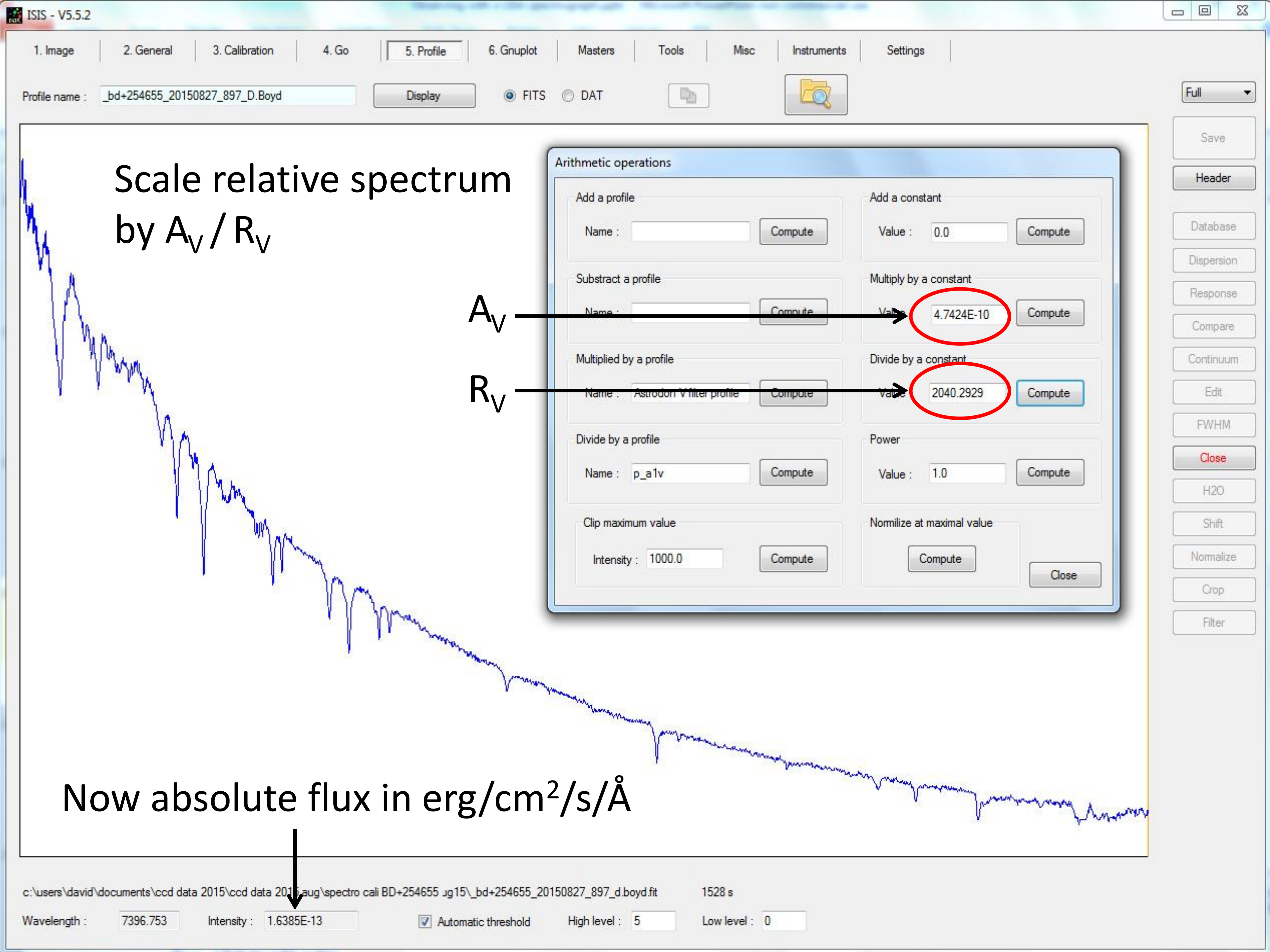
- To get the absolute flux spectrum of BD+25 4655 we scale the relative flux spectrum by A_V / R_V

- This is straightforward to implement in ISIS.

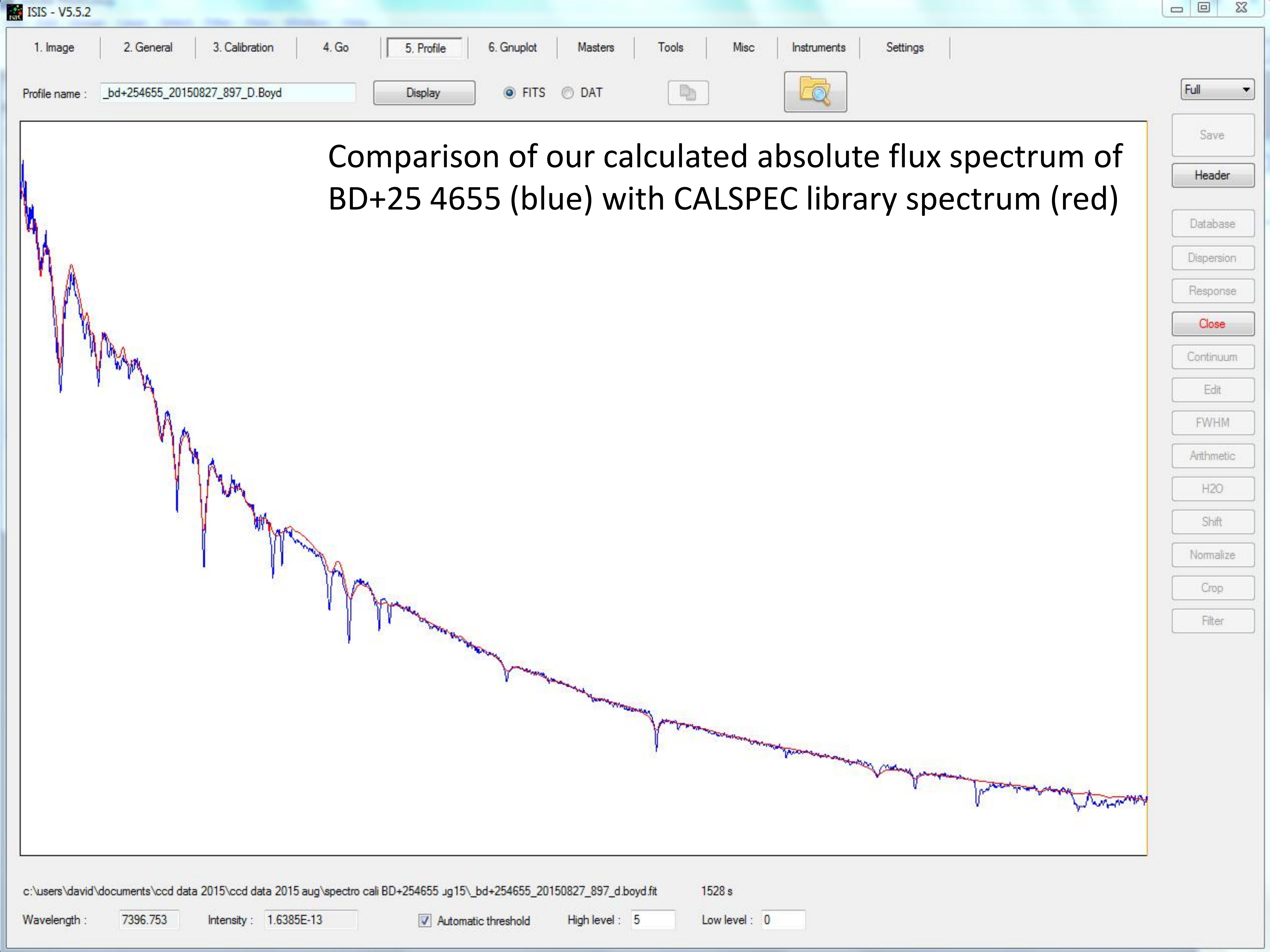

ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name :
_bd+254655_20150827_897_D.Boyd
Display
FITS
DAT
Full
Measured relative flux spectrum of BD+25 4655
Save
Header
Database
Dispersion
Response
Compare
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
c:\users\david\documents\ccd data 2015\ccd data 2015 aug\spectro cali BD+254655 ug15_bd+254655_20150827_897_d.boyd.fit
1528 s
Wavelength :
7396.753
Intensity :
0.704918
Automatic threshold
High level :
5
Low level :
0

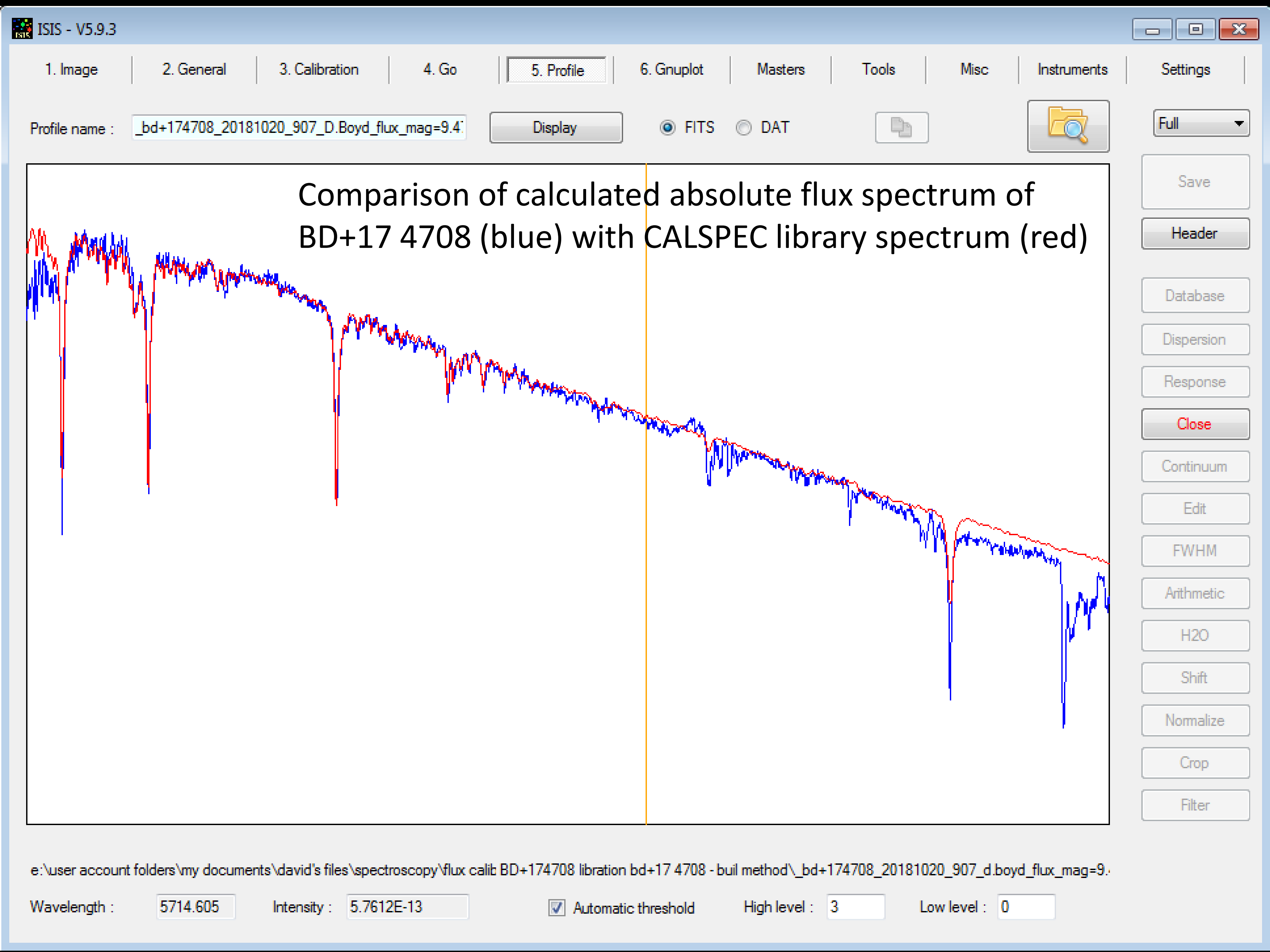
Relative V-band flux R_V

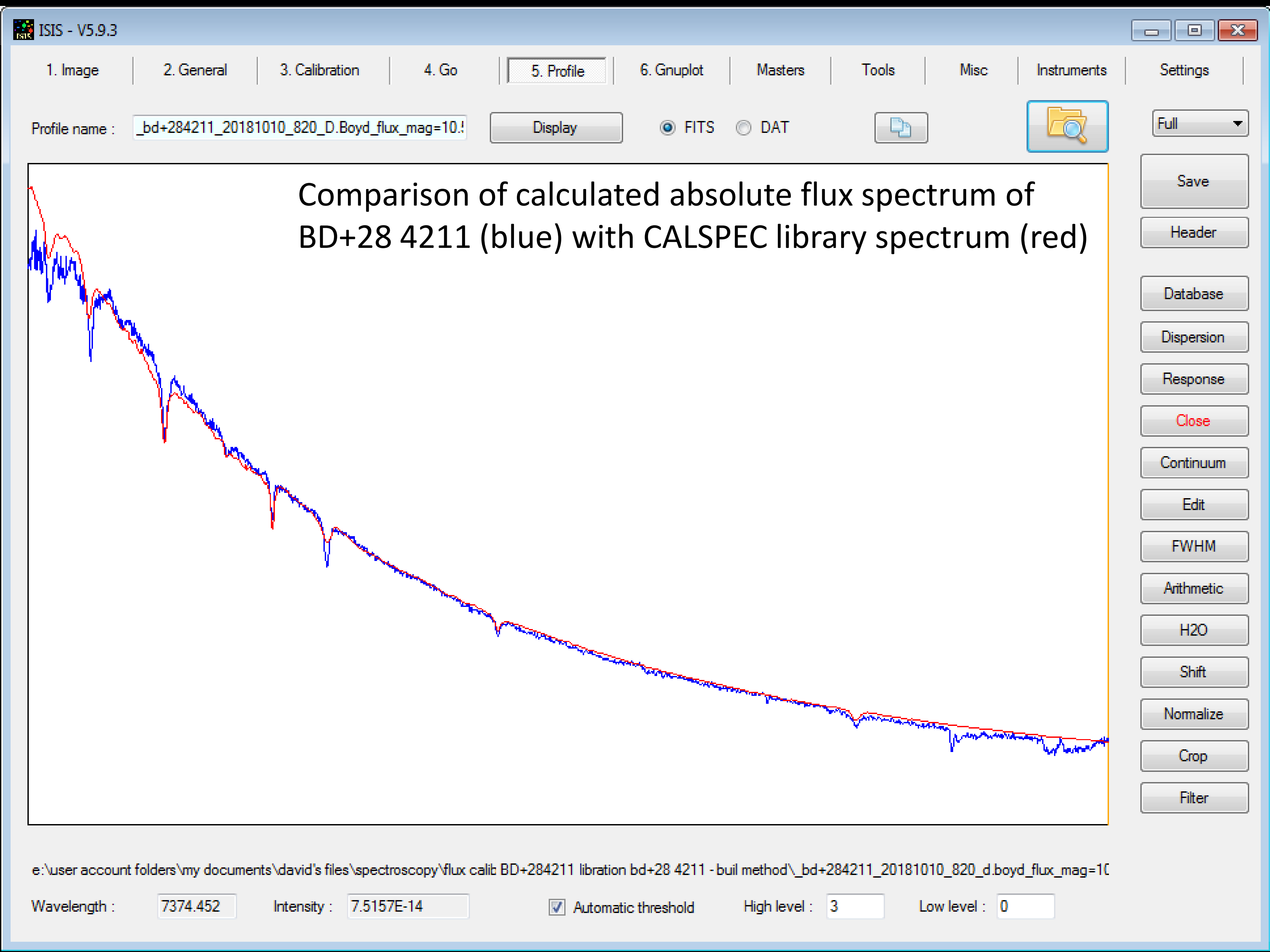


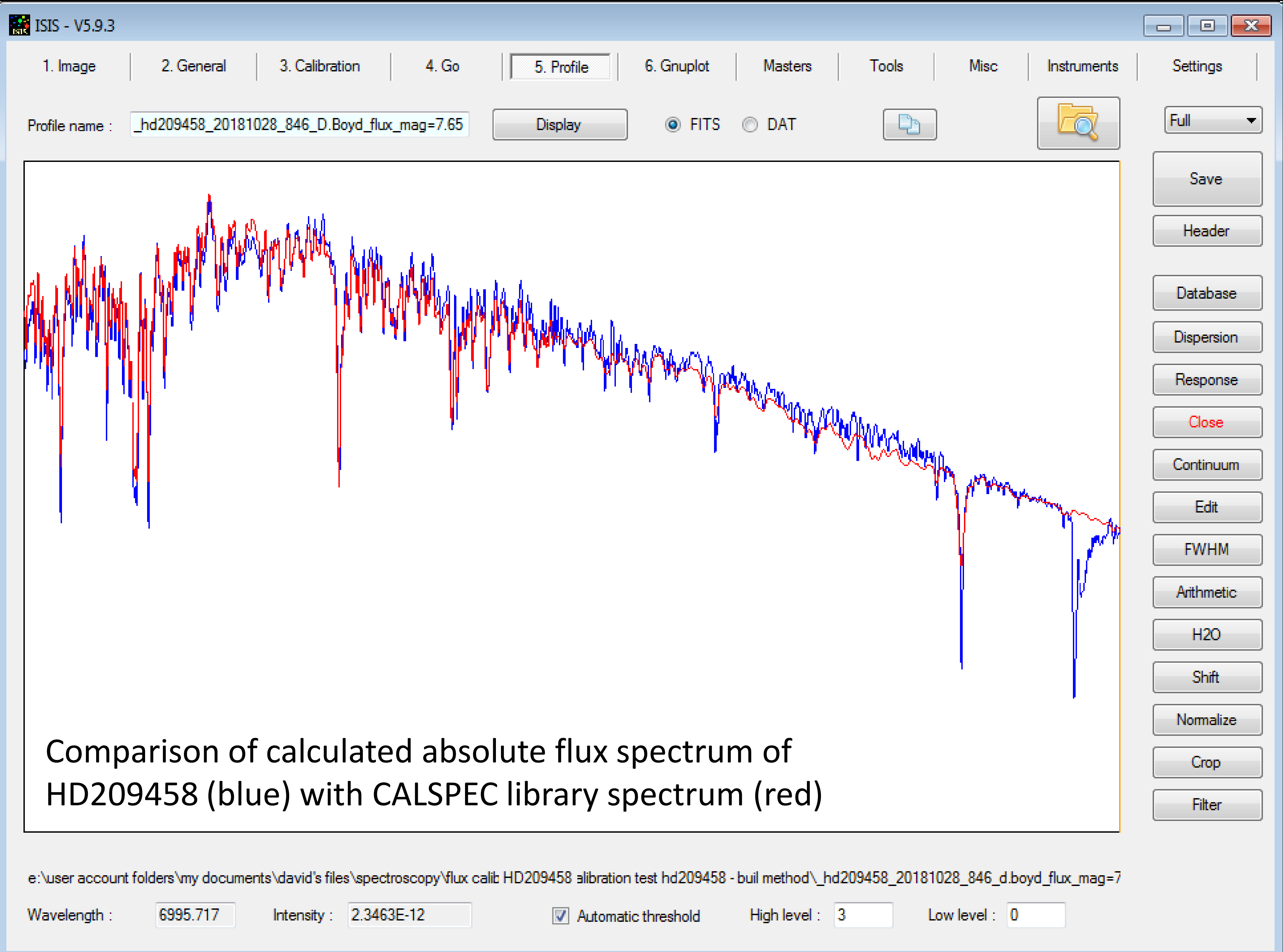


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name : _bd+254655_20150827_897_D.Boyd
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Compare
Continuum
Edit
FWHM
Close
H2O
Shift
Normalize
Crop
Filter
Scale relative spectrum
by A_V / R_V
Arithmetic operations
Add a profile
Name :
Compute
Add a constant
Value : 0.0
Compute
Substract a profile
Name :
Compute
Multiply by a constant
Value : 4.7424E-10
Compute
A_V
Multiplied by a profile
Name : Astrodon V filter profile
Compute
Divide by a constant
Value : 2040.2929
Compute
R_V
Divide by a profile
Name : p_a1v
Compute
Power
Value : 1.0
Compute
Clip maximum value
Intensity : 1000.0
Compute
Nomilize at maximal value
Compute
Close
Now absolute flux in erg/cm²/s/Å
c:\users\david\documents\ccd data 2015\ccd data 2015 aug\spectro cali BD+254655 aug15_bd+254655_20150827_897_d.boyd.fit
1528 s
Wavelength : 7396.753
Intensity : 1.6385E-13
Automatic threshold
High level : 5
Low level : 0


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name :
_bd+254655_20150827_897_D.Boyd
Display
FITS
DAT
Full
Comparison of our calculated absolute flux spectrum of BD+25 4655 (blue) with CALSPEC library spectrum (red)
Save
Header
Database
Dispersion
Response
Close
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
c:\users\david\documents\ccd data 2015\ccd data 2015 aug\spectro cali BD+254655 ɹg15_bd+254655_20150827_897_d.boyd.fit
1528 s
Wavelength :
7396.753
Intensity :
1.6385E-13
Automatic threshold
High level :
5
Low level :
0


ISIS - V5.9.3
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name :
_bd+174708_20181020_907_D.Boyd_flux_mag=9.4
Display
FITS
DAT
Full
Comparison of calculated absolute flux spectrum of
BD+17 4708 (blue) with CALSPEC library spectrum (red)
Save
Header
Database
Dispersion
Response
Close
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
e:\user account folders\my documents\david's files\spectroscopy\flux calib BD+174708 libration bd+17 4708 - buil method_bd+174708_20181020_907_d.boyd_flux_mag=9.
Wavelength :
5714.605
Intensity :
5.7612E-13
Automatic threshold
High level :
3
Low level :
0


ISIS - V5.9.3
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name :
_bd+284211_20181010_820_D.Boyd_flux_mag=10.!
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Close
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Comparison of calculated absolute flux spectrum of BD+28 4211 (blue) with CALSPEC library spectrum (red)
e:\user account folders\my documents\david's files\spectroscopy\flux calit BD+284211 libration bd+28 4211 - buil method_bd+284211_20181010_820_d.boyd_flux_mag=1(
Wavelength :
7374.452
Intensity :
7.5157E-14
Automatic threshold
High level :
3
Low level :
0



Comparison of calculated absolute flux spectrum of HD209458 (blue) with CALSPEC library spectrum (red)

Measuring the necessary V magnitude

The stars we can examine spectroscopically are relatively bright.

A small refractor fitted with a V filter piggy-backed on the telescope carrying your spectroscope is capable of providing a V magnitude with a SNR of ~100 to use for flux calibrating your spectra.

Measuring absolute flux – one thing to note

There is one subtlety about using a V magnitude which is worth mentioning.

As the spectrum which is being convolved with the V filter has been corrected for atmospheric extinction, strictly speaking the measured V magnitude should also be corrected for atmospheric extinction and transformed to the Johnson V standard photometric system.

You can do this by using both B and V filters and applying the appropriate transformation.

Here are the techniques I use for doing this:

Boyd, *An Alternative Approach for Finding and Applying Extinction-corrected Magnitude Transformations*, Society for Astronomical Sciences, 30th Annual Symposium on Telescope Science (2011)
http://adsabs.harvard.edu/abs/2011SASS...30..127B

Boyd, *A practical approach to transforming magnitudes onto a standard photometric system*, Journal of the AAVSO, 40.2, 990 (2012)
http://adsabs.harvard.edu/abs/2012JAVSO..40..990B

Measuring absolute flux – another thing to note

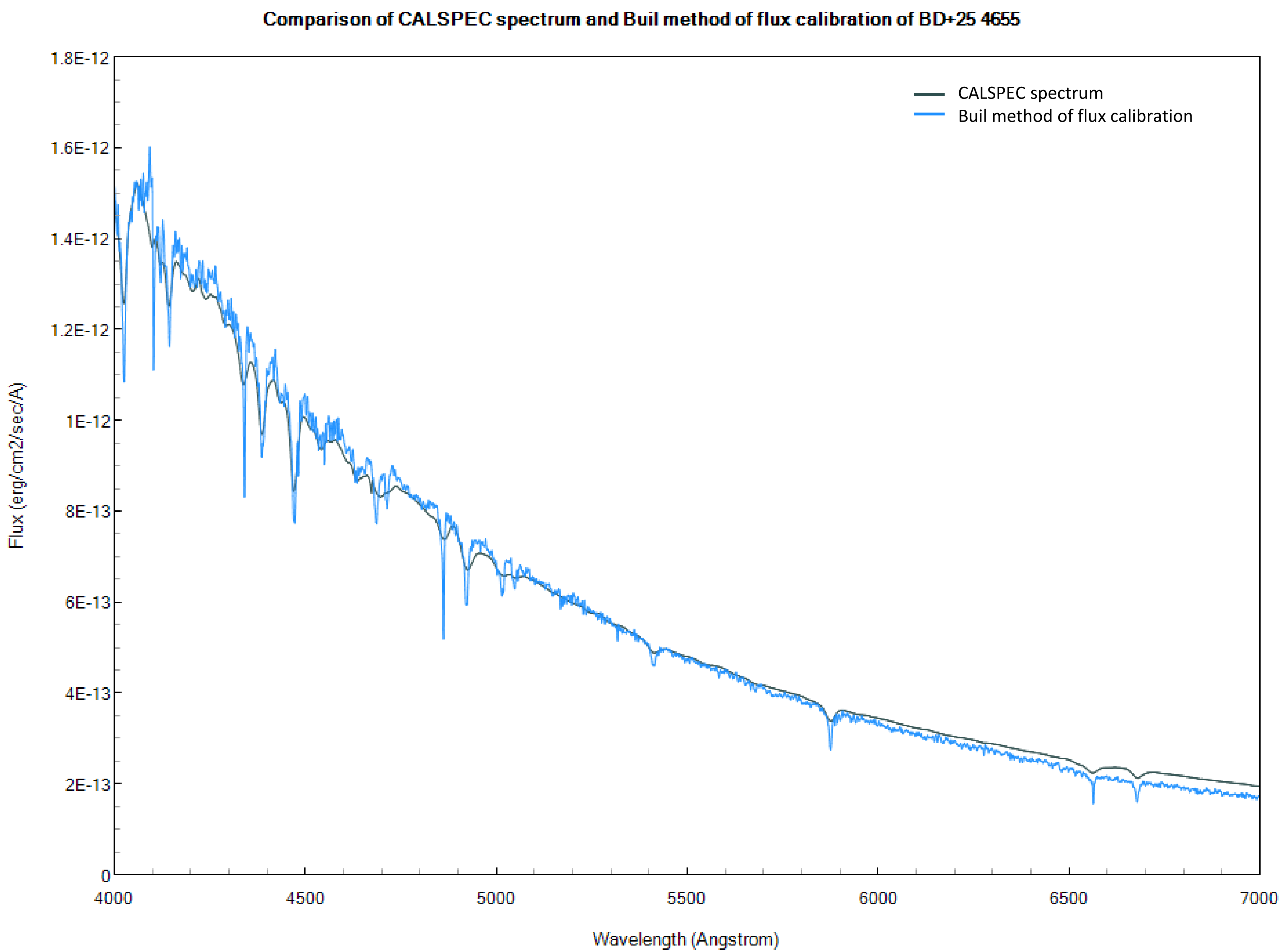
In theory a wide slit should be used to ensure no flux is lost.

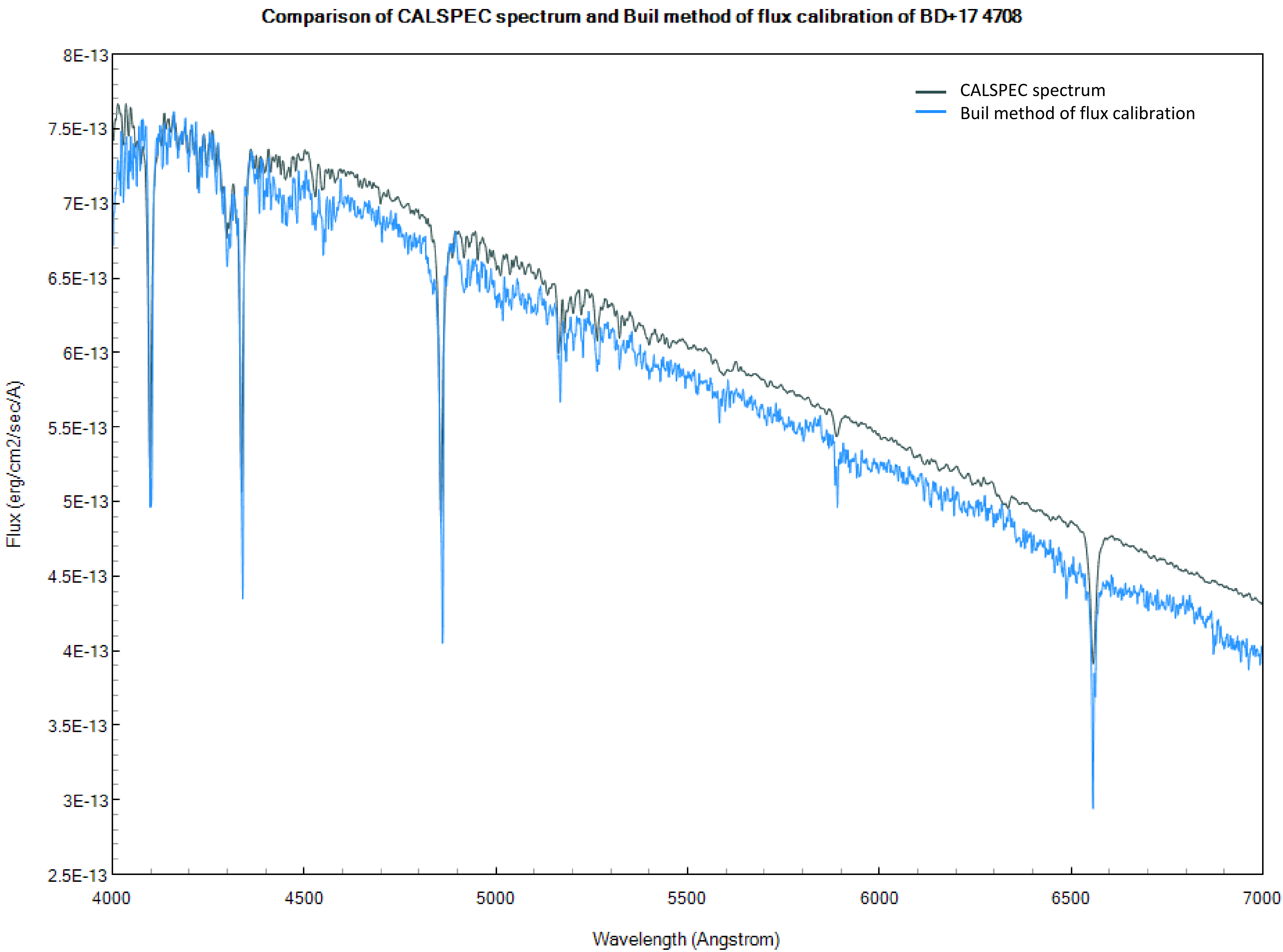
In practice, with the narrow slit which is normally used for good resolution, the measurements of both the reference and target stars experience the same small slit losses which should cancel out.

Longer exposures help to mitigate the issue by averaging the effect of seeing variations and guiding imperfections.

Also, the V filter bandpass is in the middle of the spectrum where the effect of atmospheric and chromatic dispersion is least.

The effect of atmospheric dispersion increases at low altitudes and, as a general rule, I don’t attempt spectrophotometry at an air mass greater than 2.


Comparison of CALSPEC spectrum and Buil method of flux calibration of BD+25 4655
CALSPEC spectrum
Buil method of flux calibration
Flux (erg/cm2/sec/A)
1.8E-12
1.6E-12
1.4E-12
1.2E-12
1E-12
8E-13
6E-13
4E-13
2E-13
0
4000
4500
5000
5500
6000
6500
7000
Wavelength (Angstrom)


Comparison of CALSPEC spectrum and Buil method of flux calibration of BD+17 4708
CALSPEC spectrum
Buil method of flux calibration
Flux (erg/cm2/sec/A)
Wavelength (Angstrom)
8E-13
7.5E-13
7E-13
6.5E-13
6E-13
5.5E-13
5E-13
4.5E-13
4E-13
3.5E-13
3E-13
2.5E-13
4000
4500
5000
5500
6000
6500
7000

Measuring absolute flux – estimating accuracy

In my experience the accuracy of Buil's method tested by measuring spectrophotometric standard stars using a narrow slit is variable, but usually gives results within 10%.

This may be because it is more sensitive to slit losses or, more likely, because it is using MILES stars as pseudo-standards and in some (many) cases these are variable stars.

I find the V magnitude method using a narrow slit is more reliably accurate, and testing it by measuring spectrophotometric standard stars it appears to be accurate to within a few percent.

We will see further evidence of the accuracy of the V magnitude method when we look at measurement of line fluxes for the symbiotic star V1329 Cyg.

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Measuring absorption and emission line flux (1)

As we saw earlier, with relative flux spectra it is only possible to measure the equivalent width of spectral lines in Å.

To measure their total flux we need to know the absolute flux level of the nearby continuum.

Total line flux = Continuum flux level x equivalent width

Continuum is measured in erg/cm^2/s/Å and EW in Å so total line flux is in erg/cm^2/s.

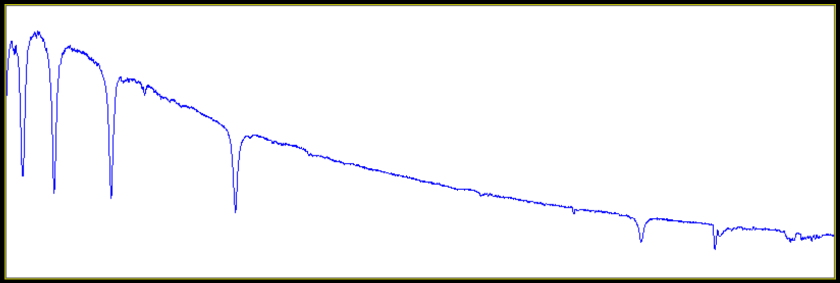
We can then monitor <u>quantitative changes</u> in the energy emission or absorption in the line over time.

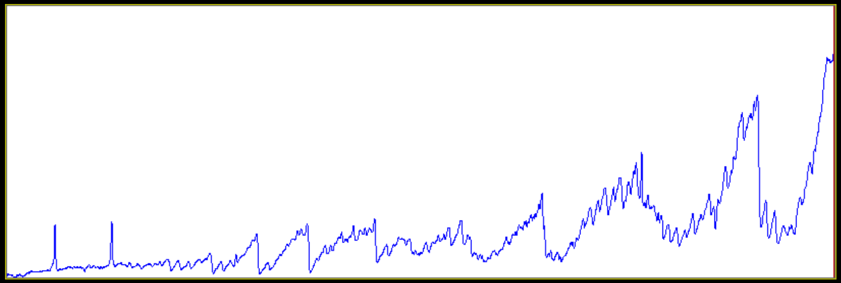
The relative uncertainty in the line flux is found by adding the relative uncertainties in the continuum level and equivalent width in quadrature.

Measuring absorption and emission line flux (2)

The first requirement is to establish the continuum level at the line.

In a spectrum with few lines, this is relatively straightforward but when there are many absorption bands this becomes difficult.





"There is as yet no generally accepted best practice in estimating the continuum level in a stellar spectrum densely populated with absorption lines."

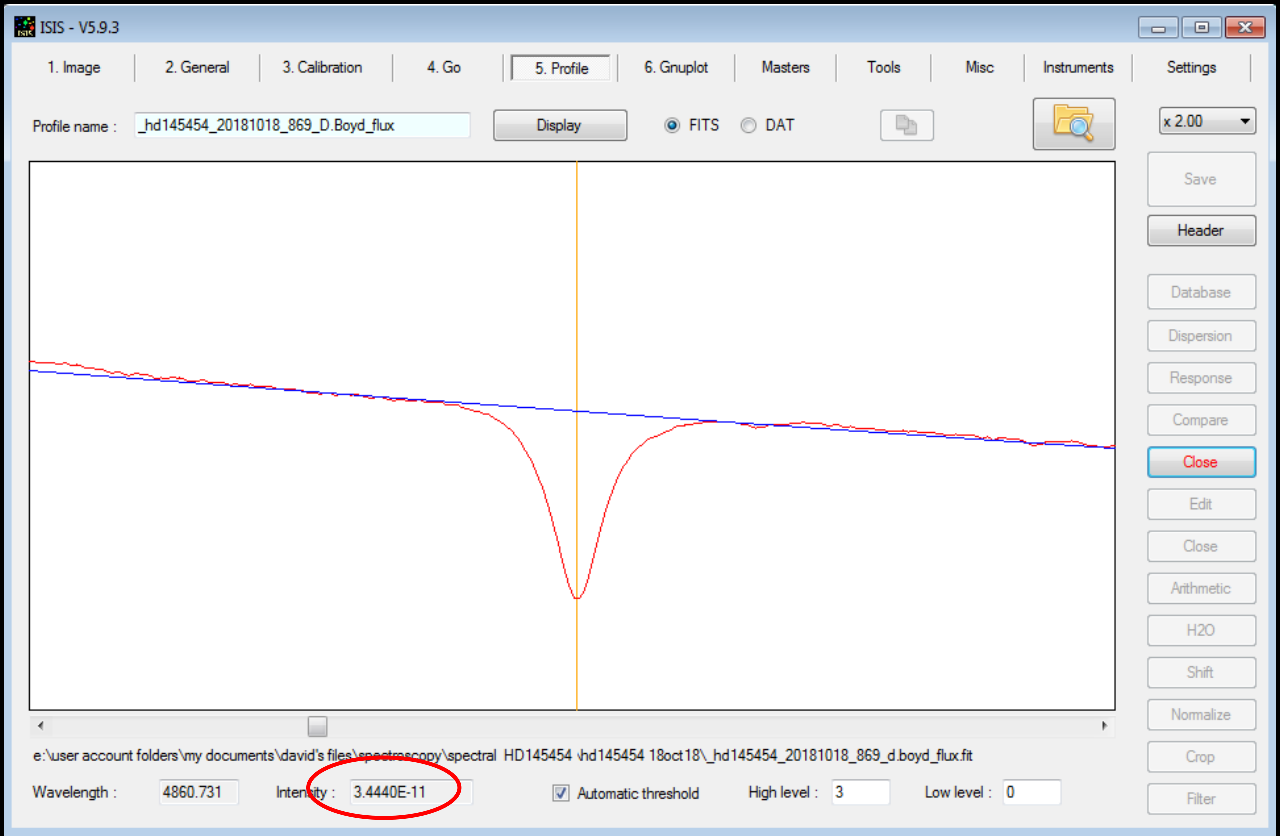
Stetson & Pancino, *DAOSPEC: An Automatic Code for Measuring Equivalent Widths in High-Resolution Stellar Spectra*, PASP, 120, 874, 1332 (2008)
http://iopscience.iop.org/article/10.1086/596126/pdf

First let's consider the simple case of single absorption or emission lines with a smooth continuum.

Measuring absorption and emission line flux (3)

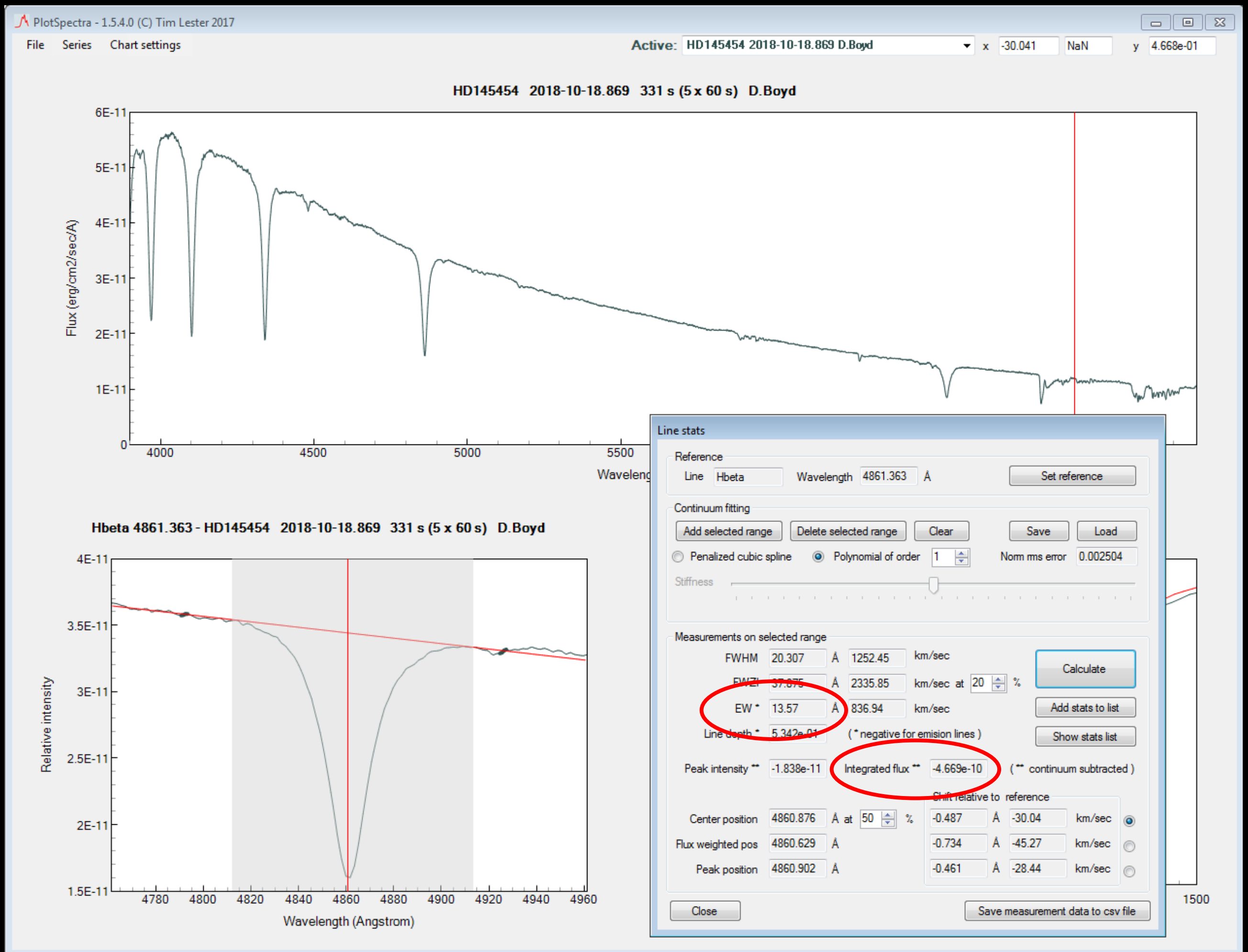
Earlier we measured the EW of the Hβ absorption line in the relative flux spectrum of the A0V star HD145454 using ISIS as 13.60 Å.

After flux calibrating this spectrum, the interpolated continuum level at the centre of the Hβ line is 3.44×10^{-11} erg/cm^2/s/Å giving a line flux of 4.68×10^{-10} erg/cm^2/s.



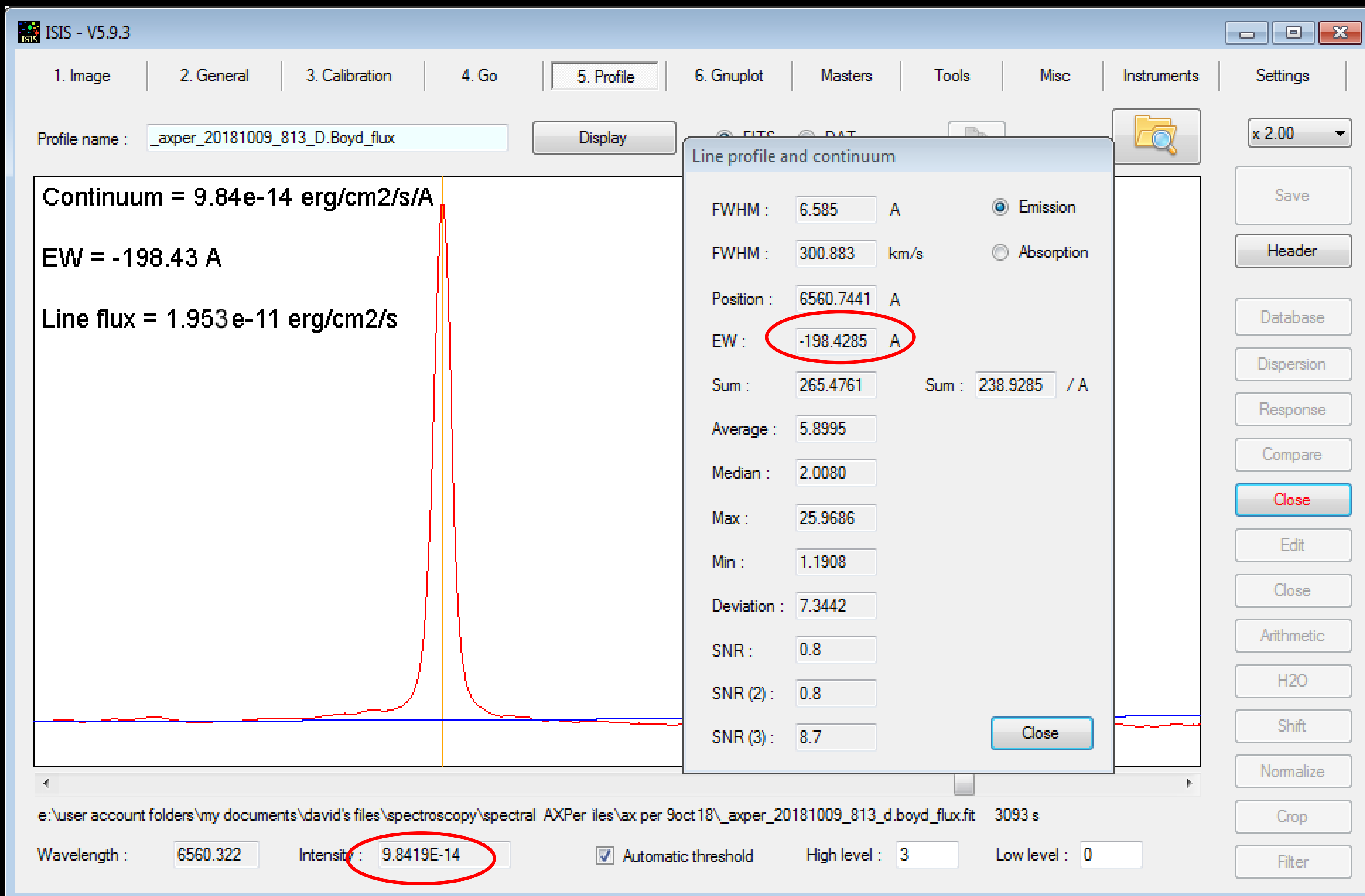
Measuring absorption and emission line flux (4)

Measuring the same flux calibrated spectrum using PlotSpectra we get an EW of 13.57 Å and a line flux of 4.67 x 10^{-10} erg/cm^2/s – good agreement.



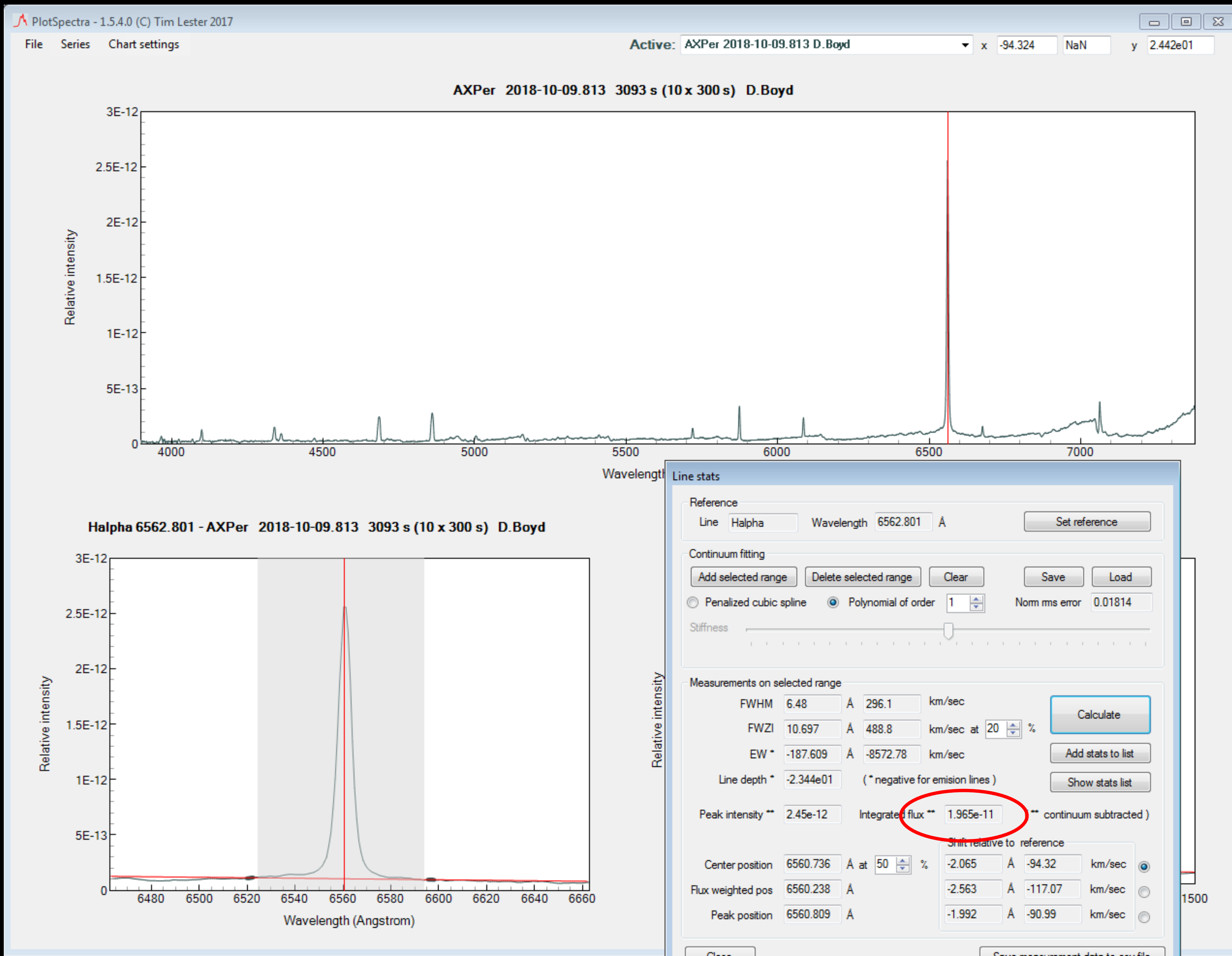
Measuring absorption and emission line flux (5)

This is the Hα emission line in the symbiotic binary AX Per measured by ISIS as 1.953×10^{-11} erg/cm^2/s . . .



Measuring absorption and emission line flux (6)

. . . and by PlotSpectra as 1.965 x 10^{-11} erg/cm^2/s.



Measuring absorption and emission line flux (7)

EW can be measured either by

a) numerically integrating the total flux between the continuum and the line profile or

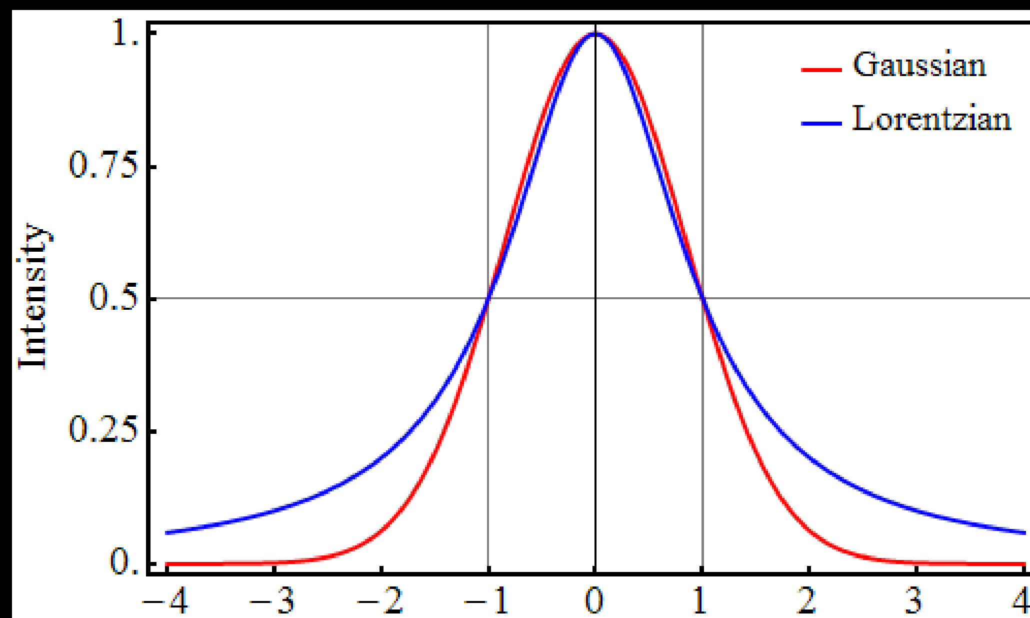
b) mathematically fitting a function to the line profile.

The most common functions are Gaussian, Lorentzian or Voigt. Voigt is a convolution of Gaussian and Lorentzian functions.

Gaussian: $$y = a_0 \exp\left[-\ln(2)\left(\frac{x-a_1}{a_2}\right)^2\right]$$

Lorentzian: $$y = \frac{a_0}{1+\left(\frac{x-a_1}{a_2}\right)^2}$$

Voigt: $$y = \frac{a_0 \int_{-\infty}^{+\infty} \frac{\exp(-t^2)}{a_3^2+(\frac{x-a_1}{a_2}-t)^2}dt}{\int_{-\infty}^{+\infty} \frac{\exp(-t^2)}{a_3^2+t^2}dt}$$



Measuring absorption and emission line flux (8)

The application fityk can be used to fit these profiles and compute total line flux.

http://fityk.nieto.pl

fityk y(x) curve fitting and data analysis

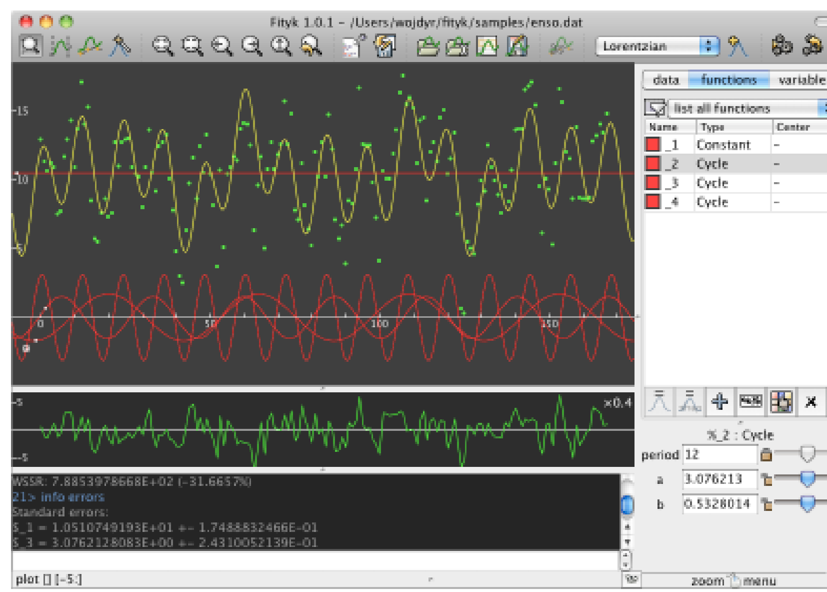
Fityk *[fi:tik]* is a program for data processing and nonlinear **curve fitting**.

Excellent GUI and command-line curve fitting tool
- John Allspaw in *The art of capacity planning*

Primarily used

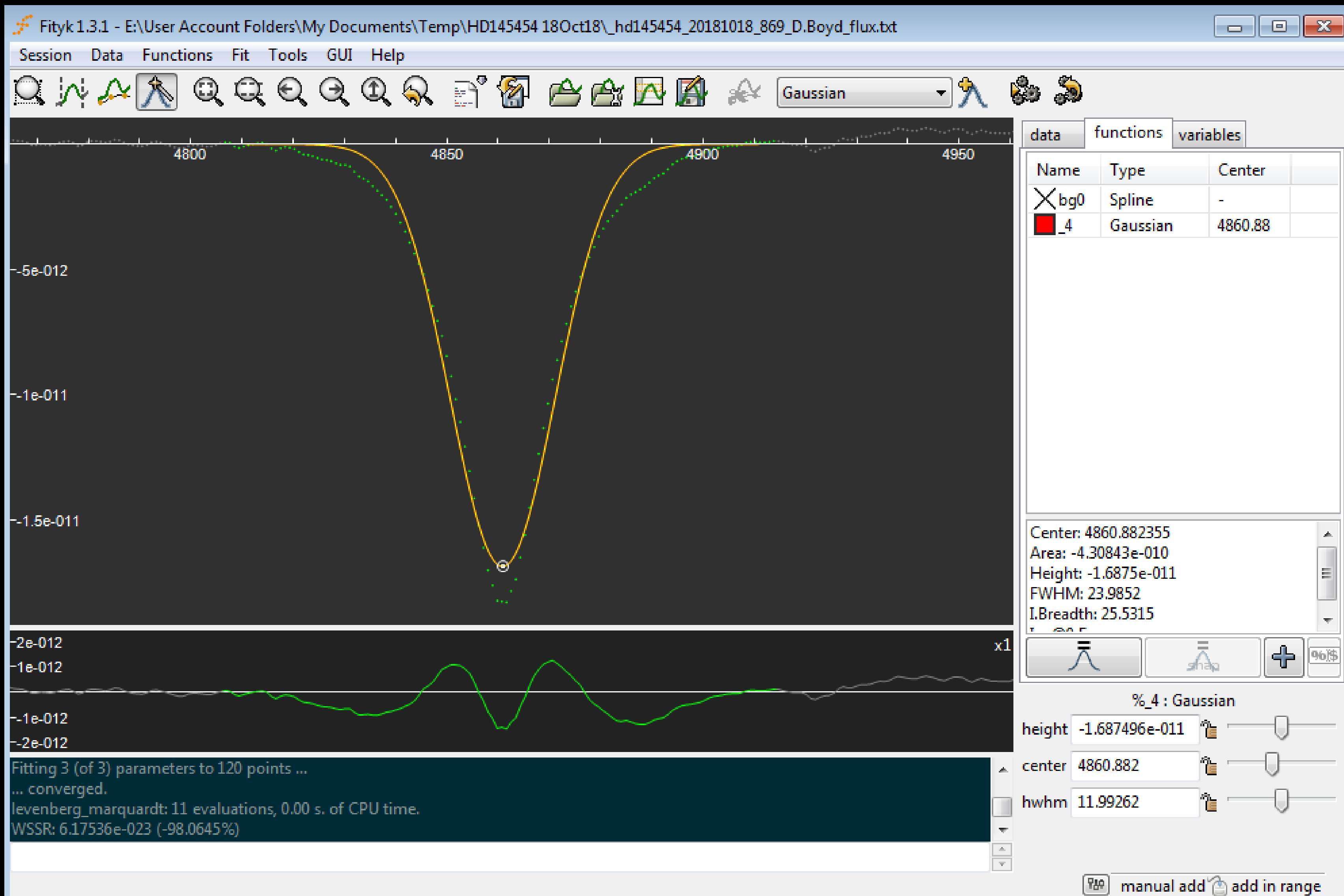
- by scientists who analyse data from powder diffraction, chromatography, photoluminescence and photoelectron spectroscopy, infrared and Raman spectroscopy, and other experimental techniques,
- to fit peaks – bell-shaped functions (Gaussian, Lorentzian, Voigt, Pearson VII, bifurcated Gaussian, EMG, Doniach-Sunjic, etc.),

but it is suitable for fitting any curve to 2D (*x*,*y*) data.



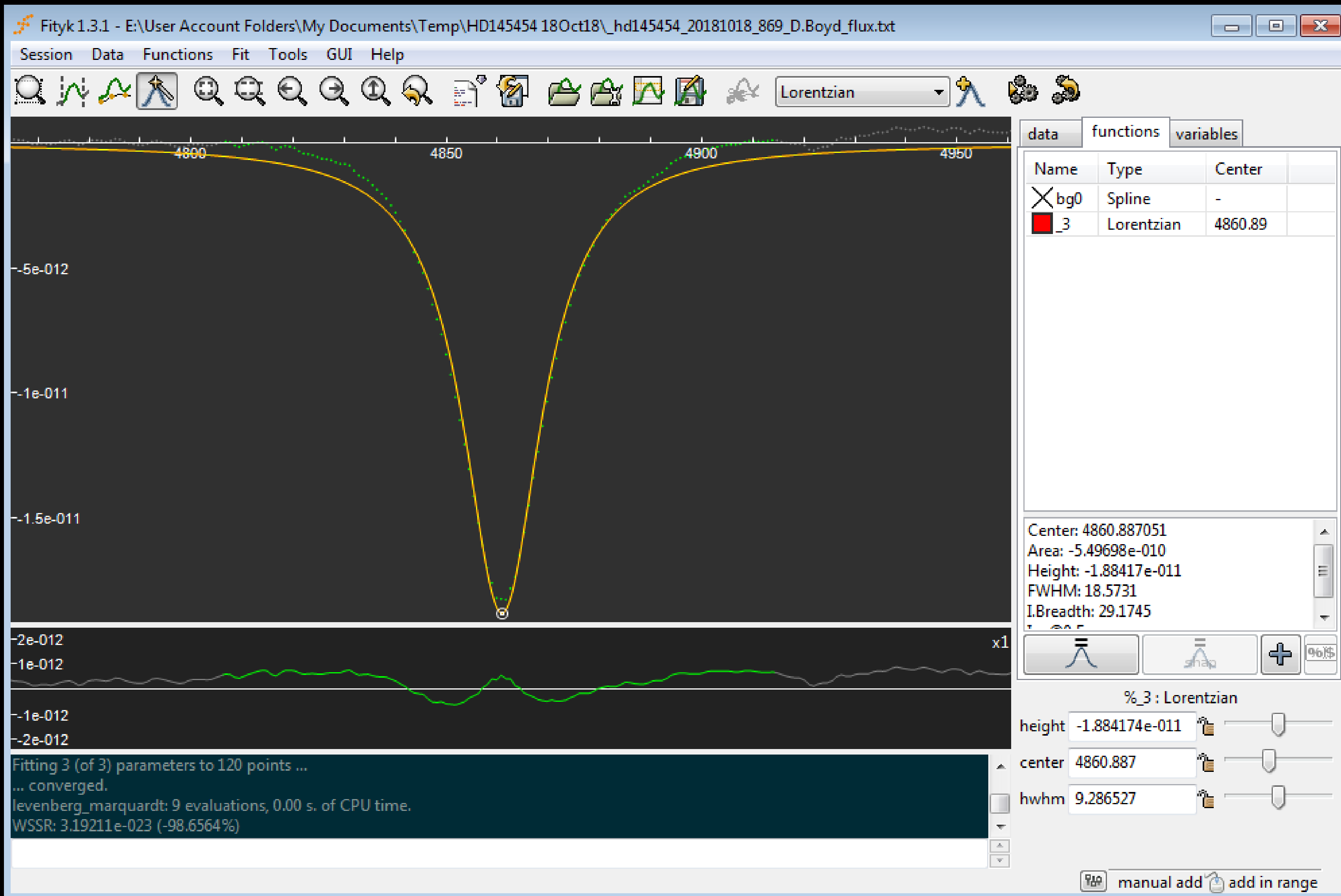
Measuring absorption and emission line flux (9)

Gaussian profile fitted with fityk –> line flux = 4.31 x 10^{-10} erg/cm^2/s



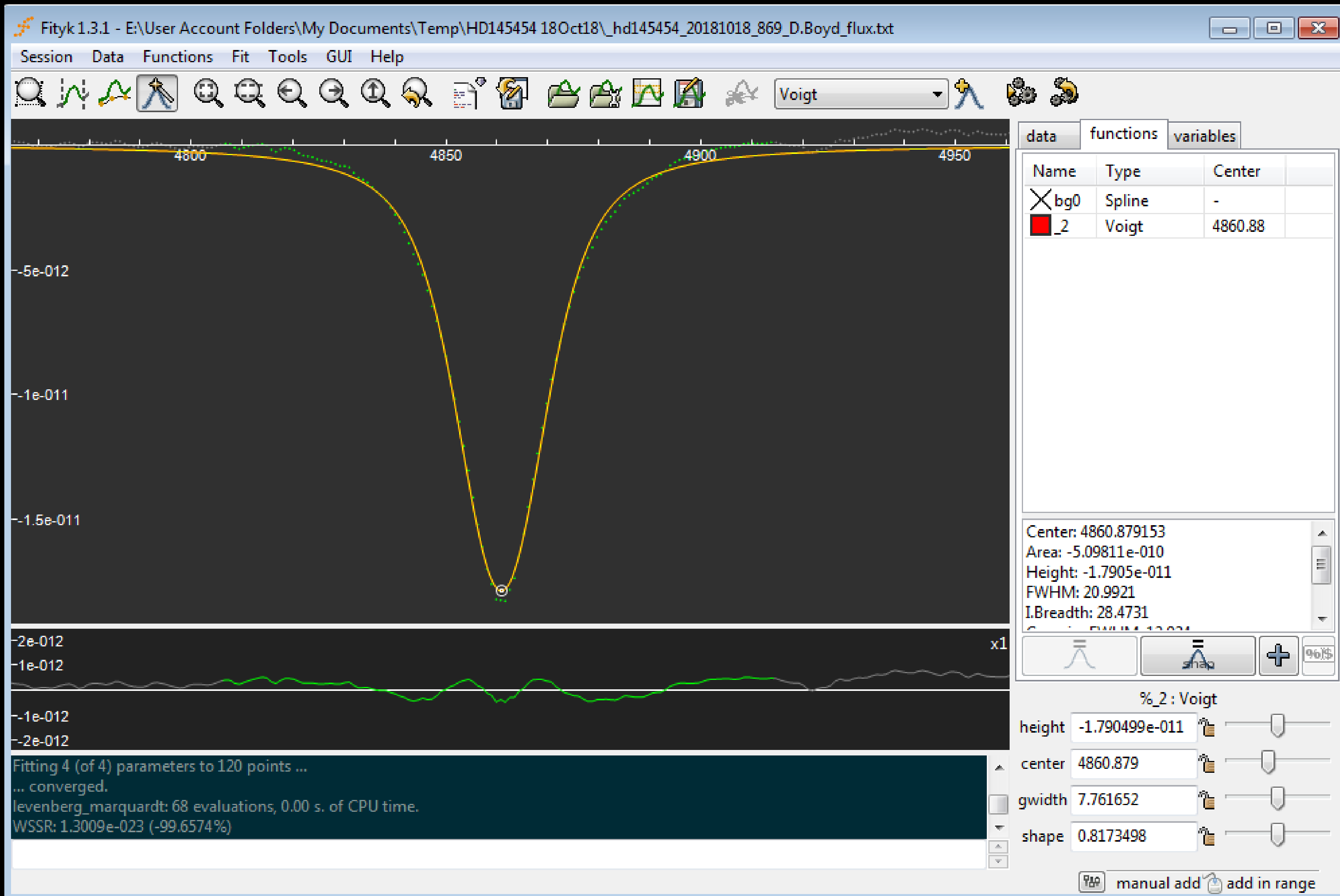
Measuring absorption and emission line flux (10)

Lorentzian profile fitted with fityk –> line flux = 5.50×10^{-10} erg/cm^2/s



Measuring absorption and emission line flux (11)

Voigt profile fitted with fityk –> line flux = 5.10 x 10^{-10} erg/cm^2/s



Measuring absorption and emission line flux (12)

Numerical integration	4.68×10^{-10} erg/cm^2/s
Gaussian	4.31×10^{-10} erg/cm^2/s
Lorentzian	5.50×10^{-10} erg/cm^2/s
Voigt	5.10×10^{-10} erg/cm^2/s

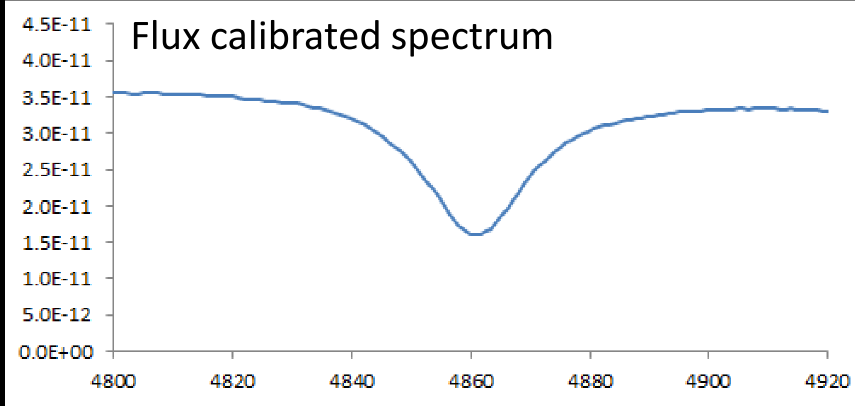
The accuracy of the calculated line flux depends on how well the mathematical function used fits the measured line profile.

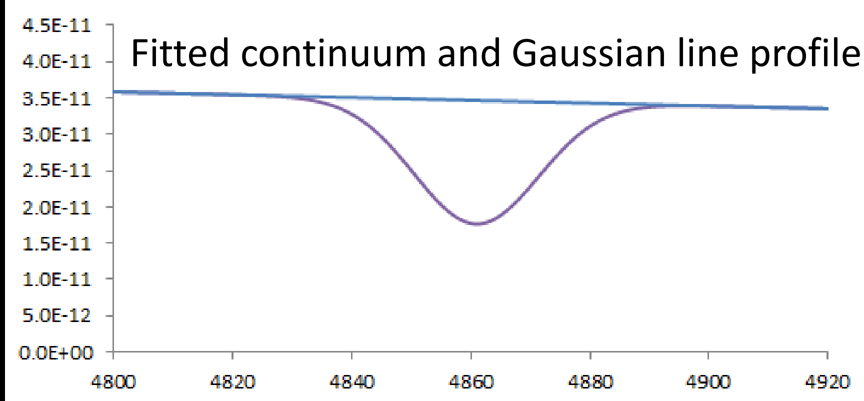
Measuring absorption and emission line flux (13)

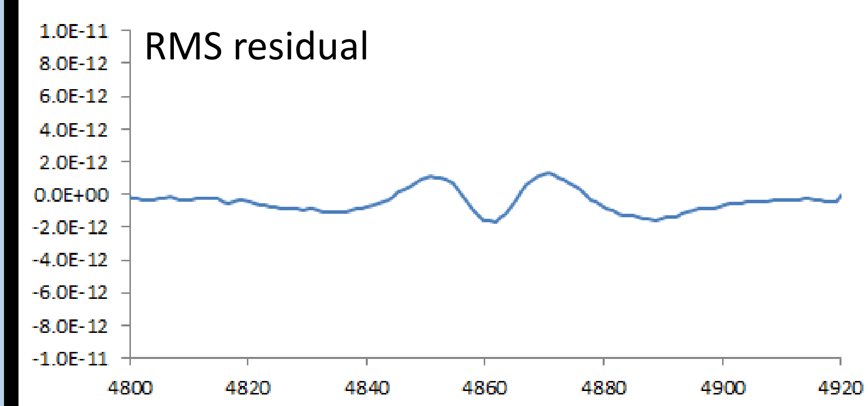
You can also use the Solver function in Excel to fit a Gaussian to the line profile.

Excel flux = 4.45 x 10^{-10} erg/cm^2/s

fityk flux = 4.31 x 10^{-10} erg/cm^2/s







Measuring absorption and emission line flux (14)

Sometimes spectral lines close in wavelength merge and form a complex line profile.

These lines may be physically unrelated or may be formed as part of complex physical processes in the star.

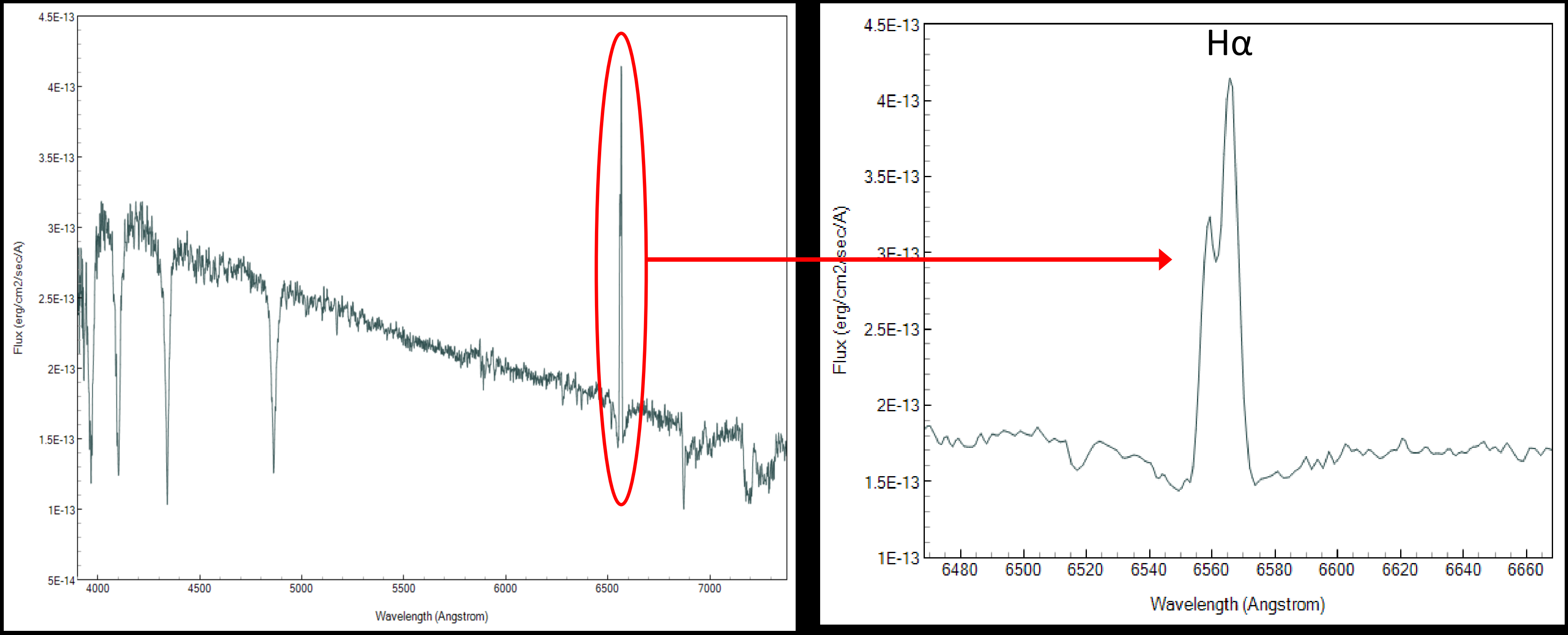
In these cases a mathematical solution is the only practical approach.

Measuring absorption and emission line flux (15)

WW Vul is a Herbig Ae star with a protoplanetary disc.

A stellar wind produces blue and red-shifted Hα emission lines in the circumstellar disc.

The broad underlying absorption line arises in the stellar photosphere.

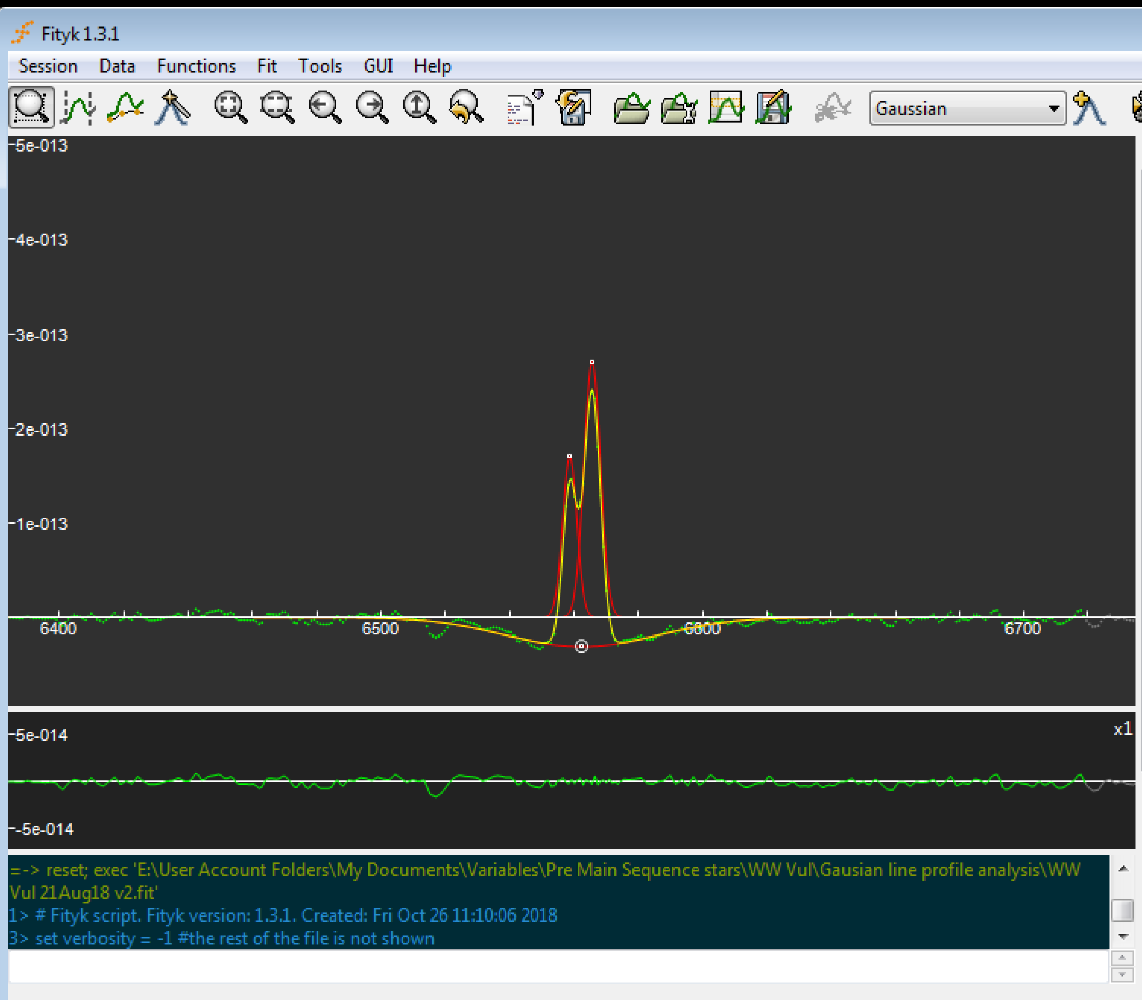


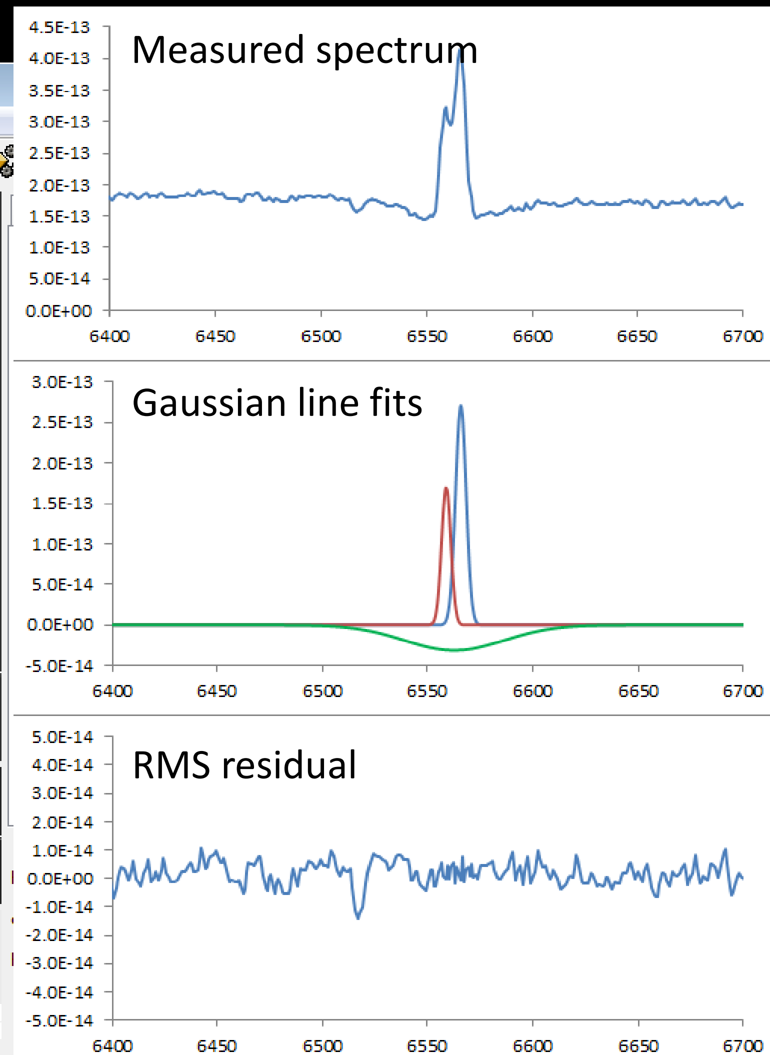
Measuring absorption and emission line flux (16)

The complex Hα emission line can be fitted with three Gaussians.

Excel Solver

fityk





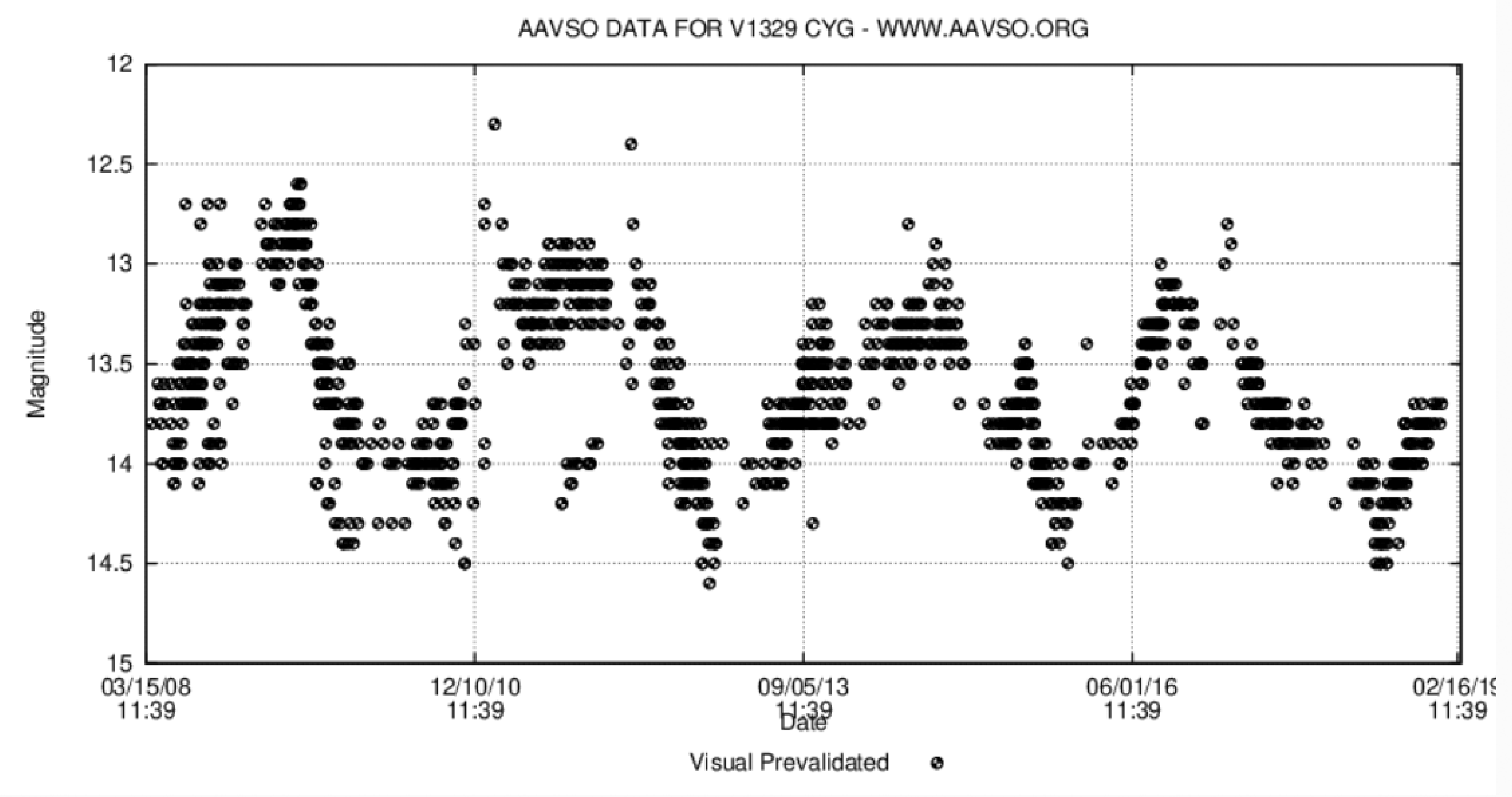
Measuring absorption and emission line flux (17)

Fitted line parameters from fityk are:

	Wavelength	Velocity	FWHM	Flux
Blue emission line	6558.7 Å	-187 km/s	5.2 Å	-1.70×10^{-13} erg/cm^2/s
Red emission line	6565.7 Å	+133 km/s	6.0 Å	-2.71×10^{-13} erg/cm^2/s
Absorption line	6562.6 Å	-9 km/s	55.9 Å	3.12×10^{-14} erg/cm^2/s

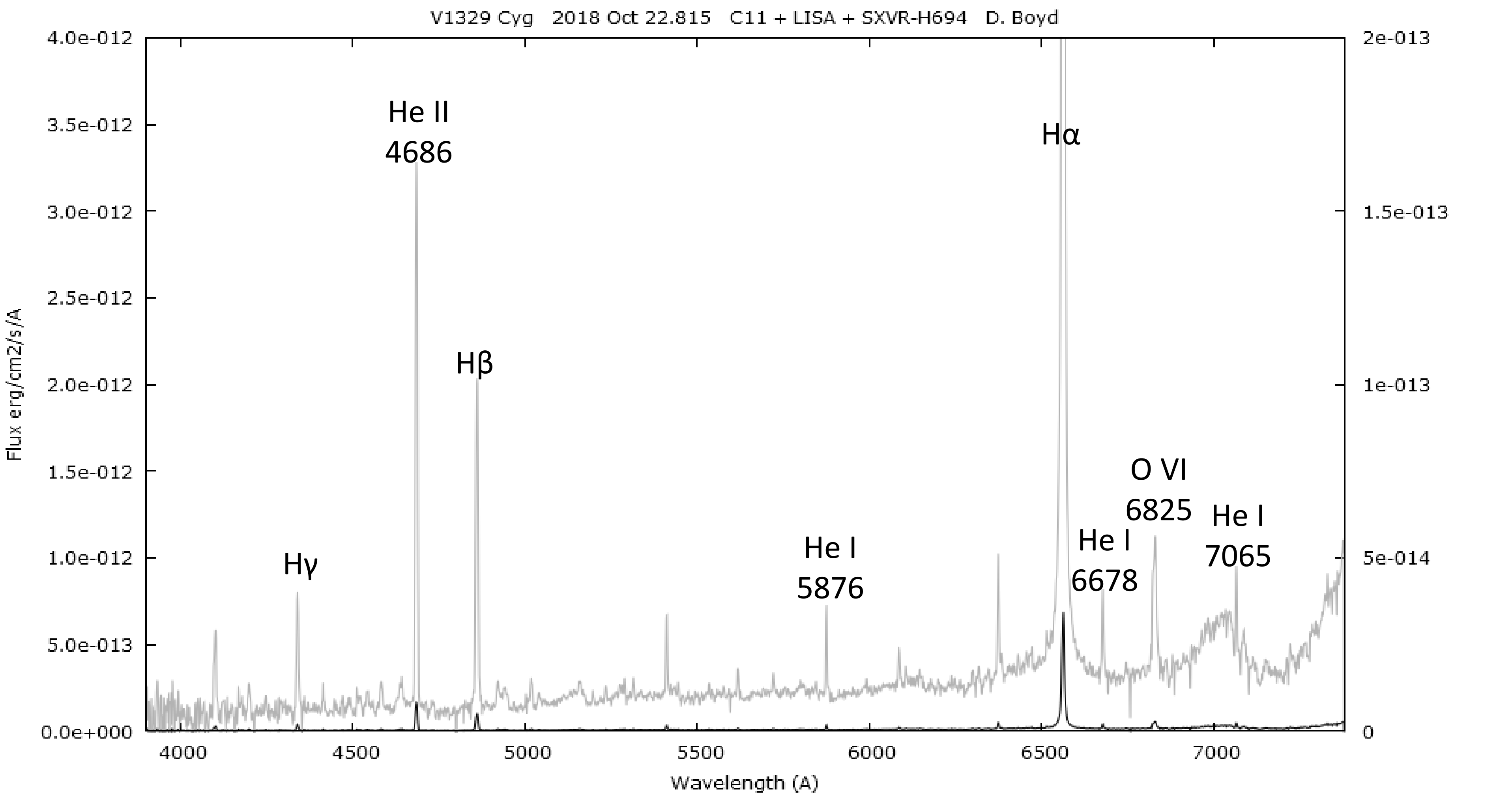
Measuring absorption and emission line flux (18)

V1329 Cyg is a symbiotic binary with orbital period 956 d and a light curve showing strong but fairly consistent orbital modulation.



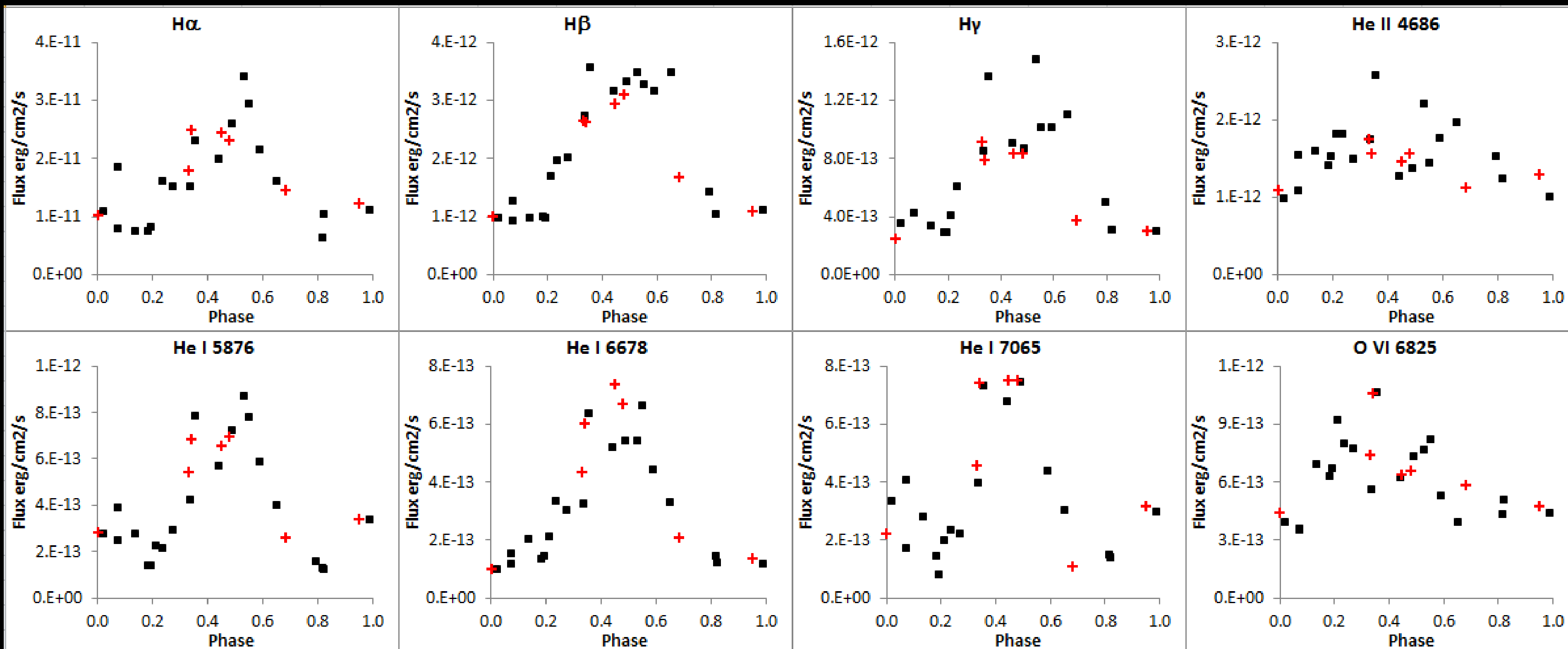
Measuring absorption and emission line flux (19)

Several emission lines generated by UV radiation from the white dwarf are formed in the surrounding nebula.



Measuring absorption and emission line flux (20)

Orbital phase plots of measured emission line fluxes compared to published data indicate the accuracy of line flux measurements.



Black points – Arkhipova et al., Astronomy Letters, 41, 128 (2015)

Red points – my measurements, 2015 - 2018

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Synthetic photometry – finding magnitudes from spectra (1)

We use the same spectroscopic zero point magnitude, ZP, that we derived before using CALSPEC absolute flux standard stars.

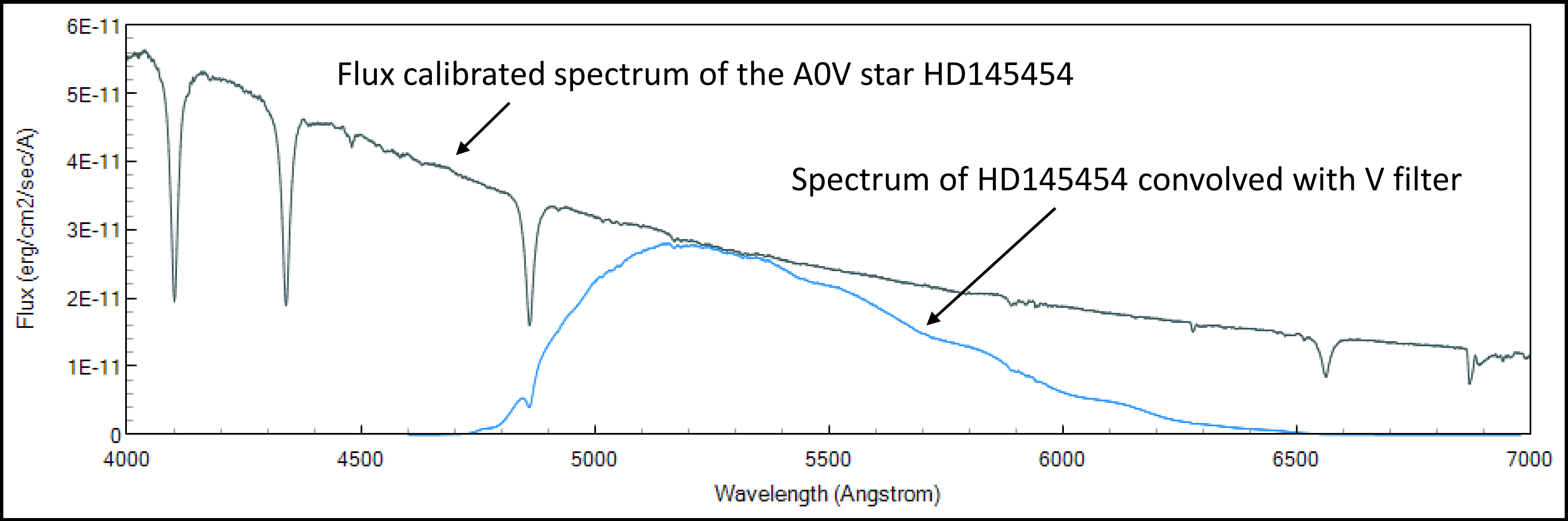
Multiply the exo-atmosphere absolute flux spectrum of the star by the V filter profile to get the flux, V flux, transmitted by the V filter for that star.

The V magnitude of the star is then given by

$$V\ mag = -2.5 * \log_{10}(V\ flux) - ZP$$

The same method can be used to find B and R magnitudes from an absolute flux spectrum provided you have transmission profiles for these filters and the spectrum extends to the wavelength limits of these filters.

Synthetic photometry – finding magnitudes from spectra (2)



Flux transmitted by V filter = $2.355*10^{-8}$ erg/cm^2/s

ZP = 13.63

V mag = $-2.5 * \log_{10}(\text{V flux}) - \text{ZP} = 5.44$

According to Simbad, V mag of HD 145454 = 5.44

The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

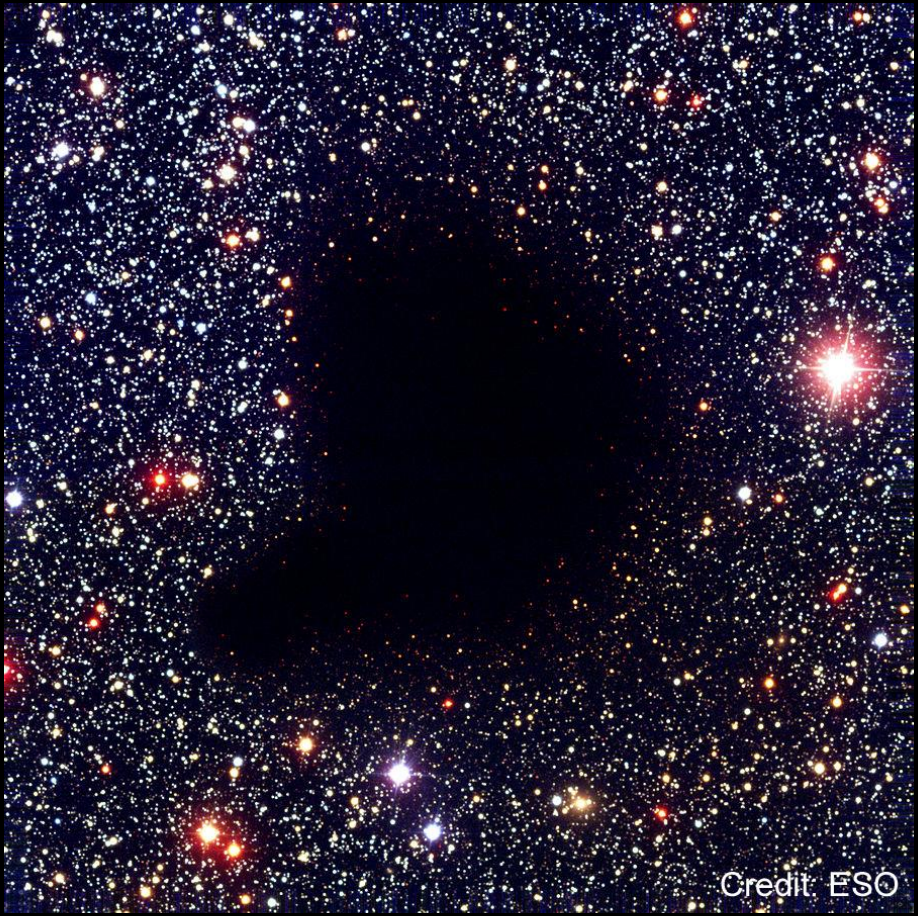
- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Interstellar extinction and reddening (1)

The extinction of starlight manifests itself in the numerous dark nebulae in our galaxy. The effect is largest in the plane of the galaxy.



Barnard 68

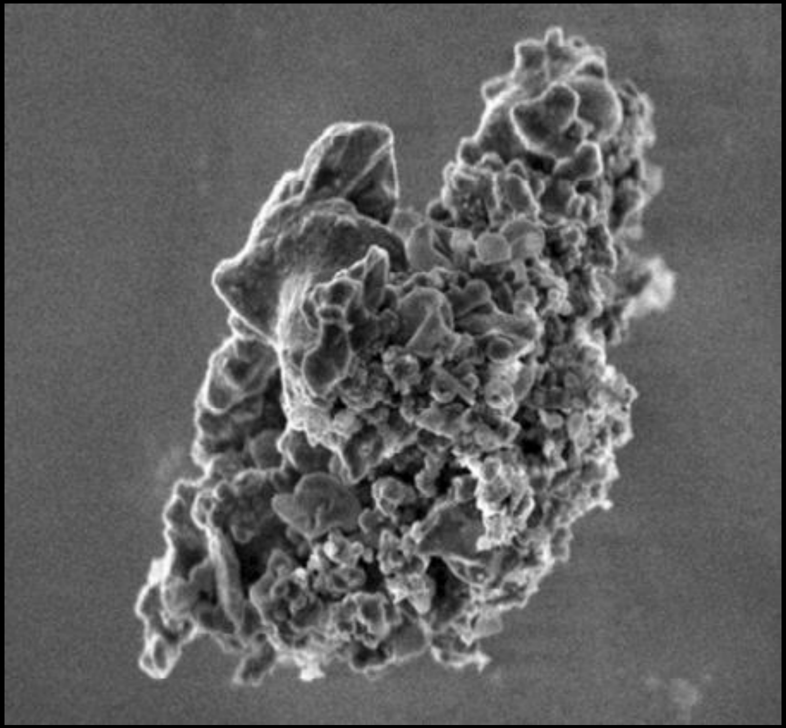
Barnard 33

Interstellar extinction and reddening (2)

Interstellar extinction is the removal of light by a combination of absorption and scattering by dust grains in the interstellar medium.

These are mainly silicates (~sand) and carbonaceous materials (~soot) and range in size from nm to µm.

Dust mainly originates from stellar outflows and aggregates over time to form larger grains.



Dust constitutes approximately 1% of the interstellar medium by mass.

Extinction varies with wavelength approximately as λ^{-1} meaning blue light is preferentially lost causing reddening.

Calculating interstellar extinction and reddening (1)

Extinction is defined in terms of the loss in light at different wavelengths.

A_λ is the total extinction or loss in magnitude at wavelength λ.

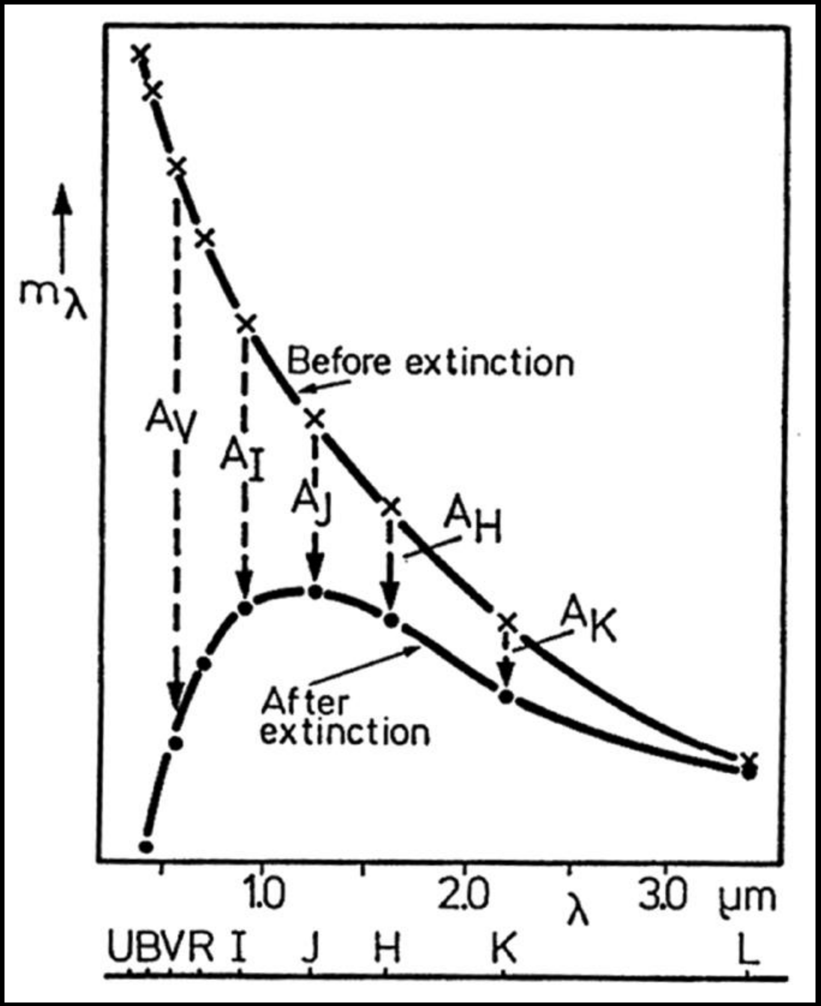
This increases at shorter wavelength.

In terms of passbands of the Johnson UBV photometry system, the total extinction in the V band is

$$A_V = V - V_0$$

where V and V_0 are the apparent (or observed) and intrinsic (or emitted) V magnitudes respectively with similar expressions for the other passbands.

$$A_V = A_\lambda \text{ at } 5500 \text{ Å}$$



Calculating interstellar extinction and reddening (2)

Selective extinction is the difference between extinction at different wavelengths.

$A_B - A_V = (B\text{-}V) - (B\text{-}V)_0 = E(B\text{-}V)$

where $(B\text{-}V)$ is the apparent colour index

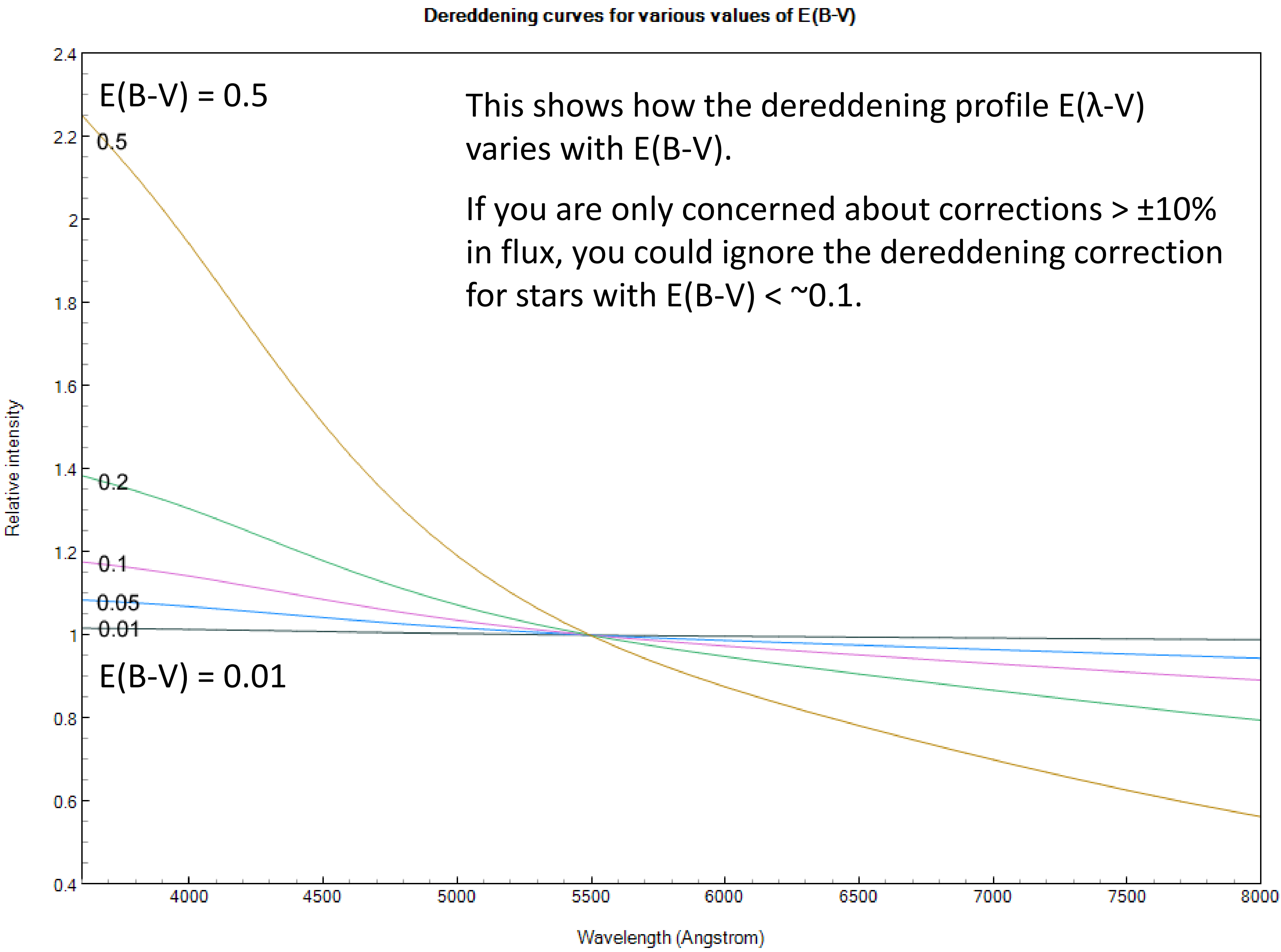
$(B\text{-}V)_0$ is the intrinsic colour index

$E(B\text{-}V)$ is the $(B\text{-}V)$ colour excess

The generalised colour excess is $E(\lambda\text{-}V) = A_\lambda - A_V$

This is known as the extinction, or dereddening, profile and defines how extinction varies as a function of wavelength.

To be able to deredden our spectrum, we need to know the extinction profile corresponding to the value of E(B-V) for our target star.



Dereddening curves for various values of E(B-V)
E(B-V) = 0.5
This shows how the dereddening profile E(λ-V) varies with E(B-V).
If you are only concerned about corrections > ±10% in flux, you could ignore the dereddening correction for stars with E(B-V) < ~0.1.
0.5
0.2
0.1
0.05
0.01
E(B-V) = 0.01
Relative intensity
Wavelength (Angstrom)
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
4000
4500
5000
5500
6000
6500
7000
7500
8000

Calculating interstellar extinction and reddening (3)

The ratio of total to selective extinction in the V band is

$$R_V = A_V / E(B-V)$$

The average value for R_V in the galactic diffuse interstellar medium is generally accepted to be $R_V = 3.1 \pm 0.1$.

However in dense molecular clouds with large grain sizes, R_V can be as large as 5 to 7.

Calculating interstellar extinction and reddening (4)

The extinction law is the variation of the relative extinction A_λ/A_V with λ.

There are different formulations of the extinction law but a popular one is that published by
J. A. Cardelli et al., *The relationship between infrared, optical, and ultraviolet extinction*, Astrophysical Journal, 345, 245 (1989)
http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1989ApJ...345..245C&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf

This has the form

$$A_\lambda/A_V = a(x) + b(x)/R_V$$

where a(x) and b(x) are parameterised as polynomials in x
with $x = 1/\lambda$ in units of μm^{-1}
and $R_V = A_V / E(B-V)$

Calculating interstellar extinction and reddening (5)

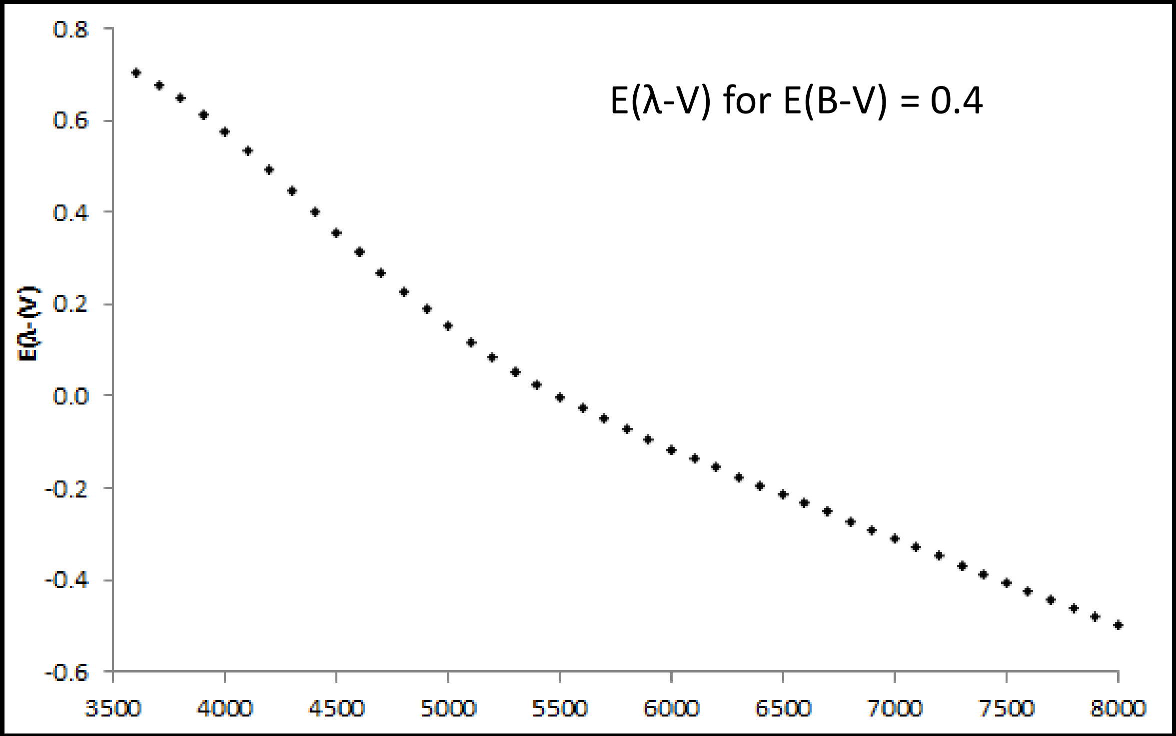
If we know E(B-V) for our star, and assume a value for R_V, we can find the total extinction in the V band A_V from

$$A_V = R_V * E(B\text{-}V)$$

Once we know A_V we can find A_λ from the extinction law for A_λ/A_V and hence the extinction or dereddening profile $E(\lambda\text{-}V) = A_\lambda - A_V$

E(λ-V) can be calculated in a spreadsheet and exported as a profile.

We can then use A_V to correct for total extinction and E(λ-V) to deredden our spectrum.



Correcting for interstellar extinction and reddening (1)

There are two distinct corrections to be made:

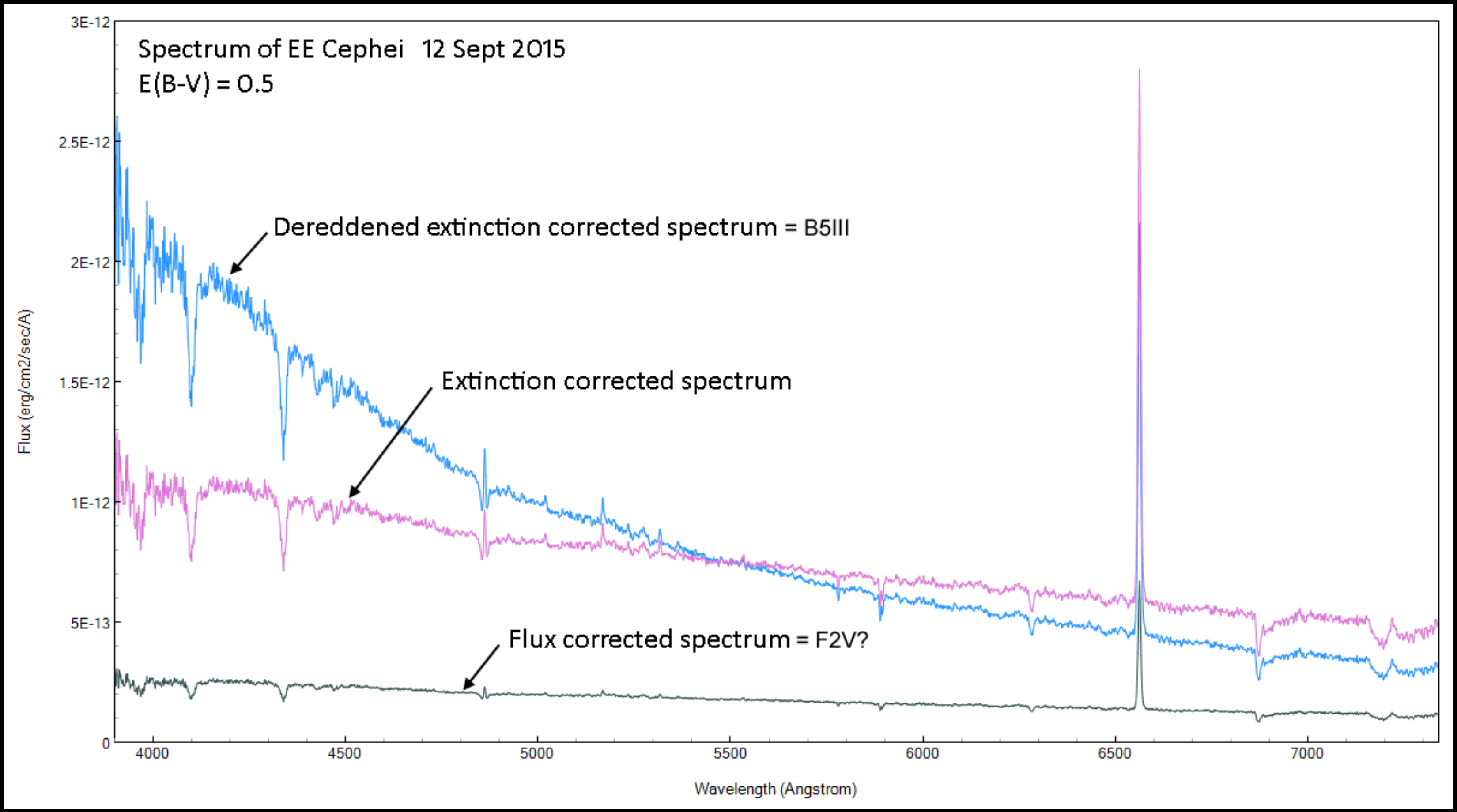
1. Correct for extinction by multiplying the absolute flux spectrum by $10^{[0.4*Av]}$
2. Correct for reddening by multiplying the spectrum by the profile $10^{[0.4*E(\lambda-V)]}$

These corrections are straightforward to apply in ISIS using its arithmetic operations capability.

Correction for interstellar reddening is important if you intend to estimate the spectral type of a star from the shape of its spectral profile, say by comparing it to spectra in a library of spectral types.

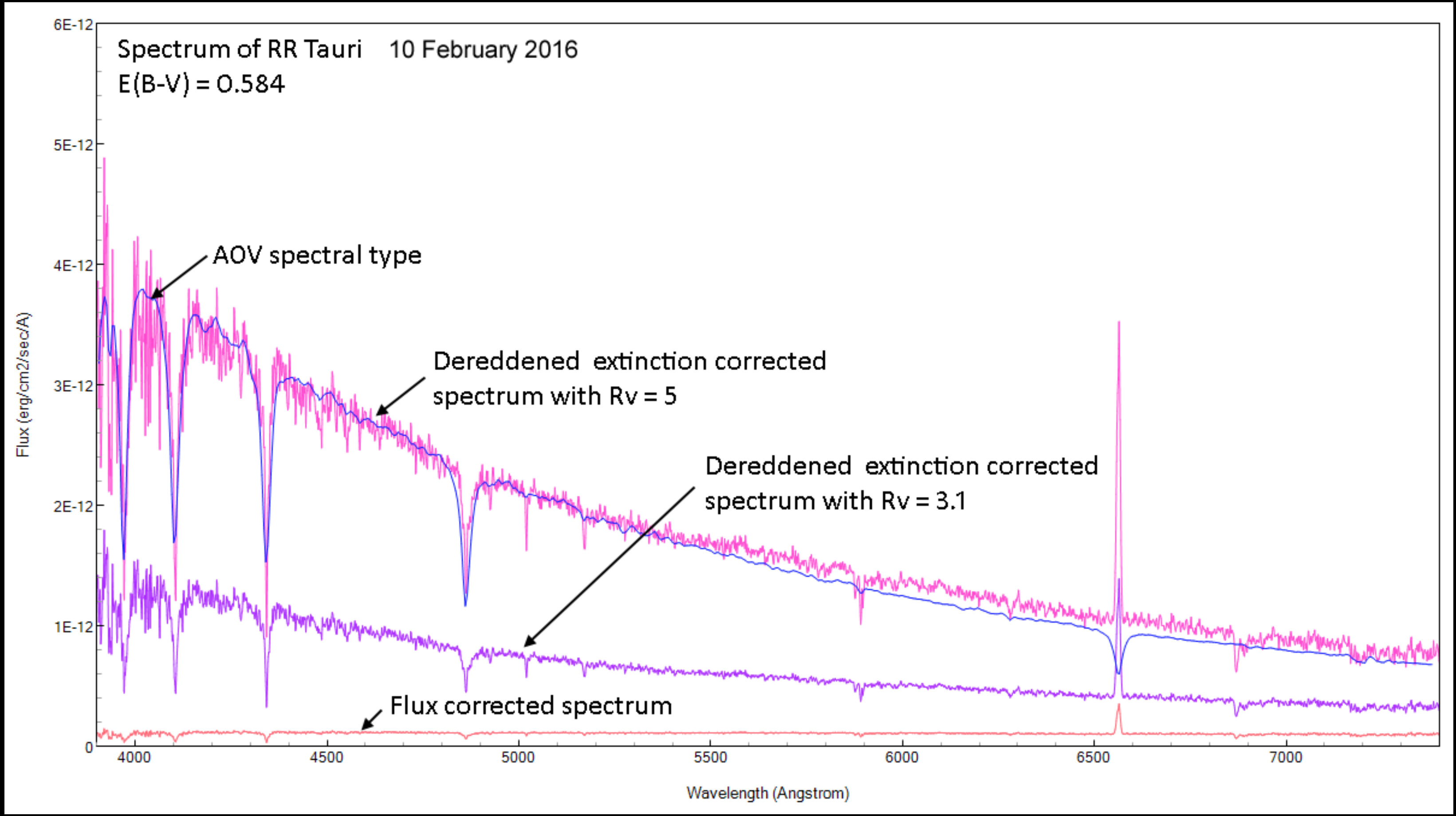
Correcting for interstellar extinction and reddening (2)

Extinction and dereddening corrections for EE Cep with E(B-V) = 0.5.
Without correction the spectral type appears to be F2V.
This is wrong – the correct spectral type of EE Cep is B5III.



Correcting for interstellar extinction and reddening (3)

The pre main sequence star RR Tauri is embedded in a dense molecular cloud containing large dust grains.
This means it has a total to selective extinction ratio $R_V = 5$.
The corrected spectrum agrees with its known spectral type A0V.



The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Determining interstellar extinction (1)

As an amateur, how can I find the extinction to an object?
You want to know either A_V or E(B-V).
There are several possible approaches.

First search published literature or databases which might report A_V or E(B-V) for the object.

Models of interstellar extinction based on 3D dust maps of the galaxy have been produced using measurements from IRAS and COBE by
D.J. Schlegel, D.P. Finkbeiner, & M. Davis , ApJ, 500, 525 (1998)
https://iopscience.iop.org/article/10.1086/305772/pdf

by analysis of the colours of stars from the Sloan Digital Sky Survey by
Schlafly and Finkbeiner, ApJ, 737, 103 (2011)
https://iopscience.iop.org/article/10.1088/0004-637X/737/2/103/pdf

and from Gaia parallaxes and PanSTARRS & 2MASS photometry by
G. M. Green et al., https://arxiv.org/pdf/1905.02734.pdf

Determining interstellar extinction (2)

3D dust maps of total galactic extinction are available at
Schlegel, Finkbeiner & Davis: https://irsa.ipac.caltech.edu/applications/DUST/
G. M. Green et al.: http://argonaut.skymaps.info

If you know the distance to the object, say with Gaia DR2, you can make a proportional estimate.

3D models of extinction in the galaxy, based on the assumption that extinction is proportional to the column density of atomic and molecular hydrogen, are published in
E. B. Amôres & J. R. D. Lépine, Astronomical Journal, 130, 659 (2005)
and available online (for Linux users) at
http://www.galextin.org/modextin.html

As a general rule of thumb, galactic extinction is ~1 mag / kpc.

Determining interstellar extinction (3)

Rectify the spectrum and comparing it with MK (Morgan & Keenan) spectral types and subtypes from
R. O. Gray & C. J. Corbally, *Stellar Spectral Classification*, Princeton University Press (2009)
or Gray's *Digital Spectral Classification Atlas*
https://ned.ipac.caltech.edu/level5/Gray/Gray_contents.html

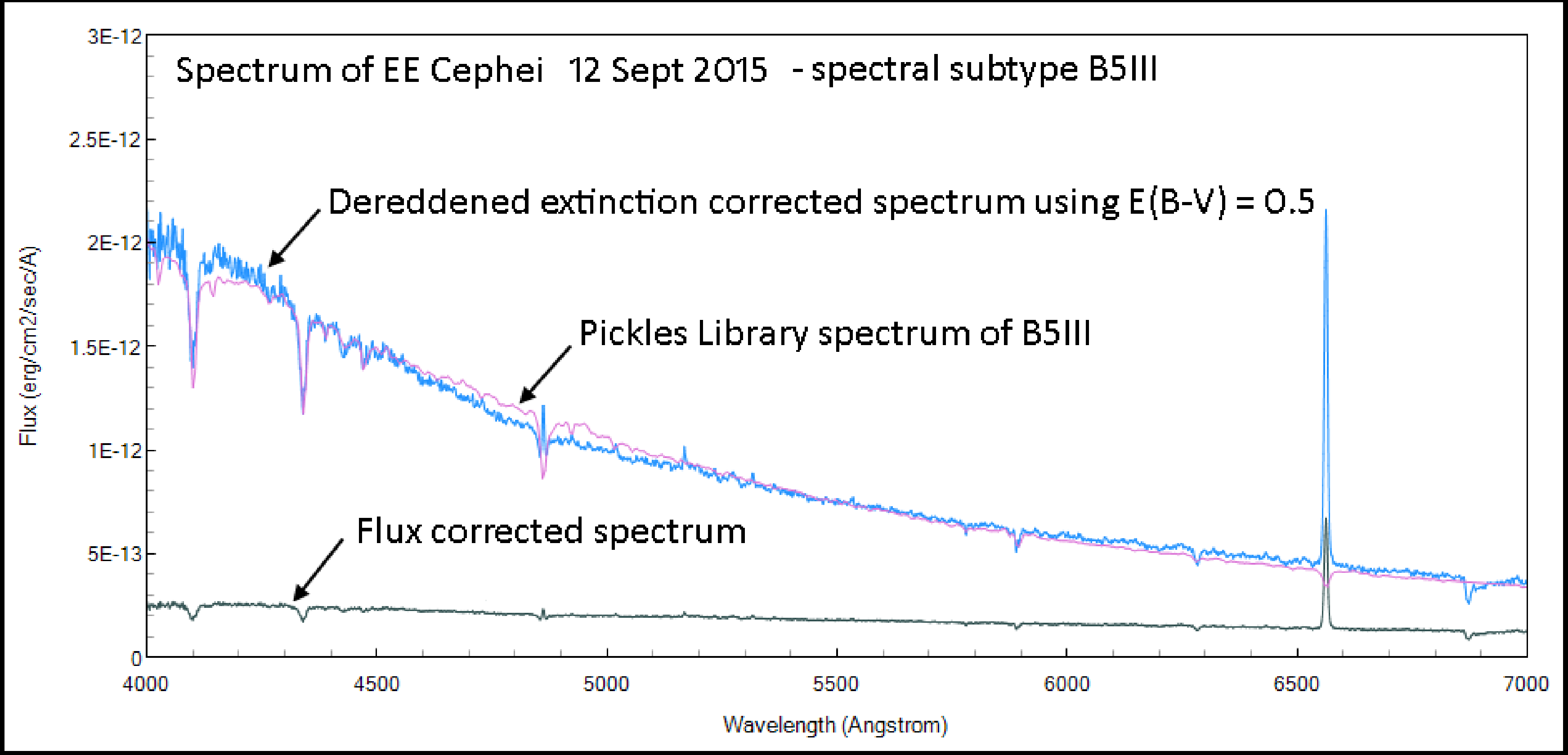
Find the reference spectral subtype which best matches the pattern of metal absorption lines in the rectified spectrum and hence infer its spectral classification.

This gives you its intrinsic colour index $(B\text{-}V)_0$ which, together with its measured apparent colour index (B-V), gives you E(B-V).

This can be checked by dereddening the observed spectral profile with this value of E(B-V) to see if it matches the inferred spectral subtype in the Pickles Stellar Spectral Flux Library.

Determining interstellar extinction (4)

On the other hand, if you know the true spectral subtype of the star from another source, you can investigate which value of E(B-V) will deredden the flux corrected spectrum to give the best match to the spectral profile of the known spectral subtype in the Pickles Library.



Determining interstellar extinction (5)

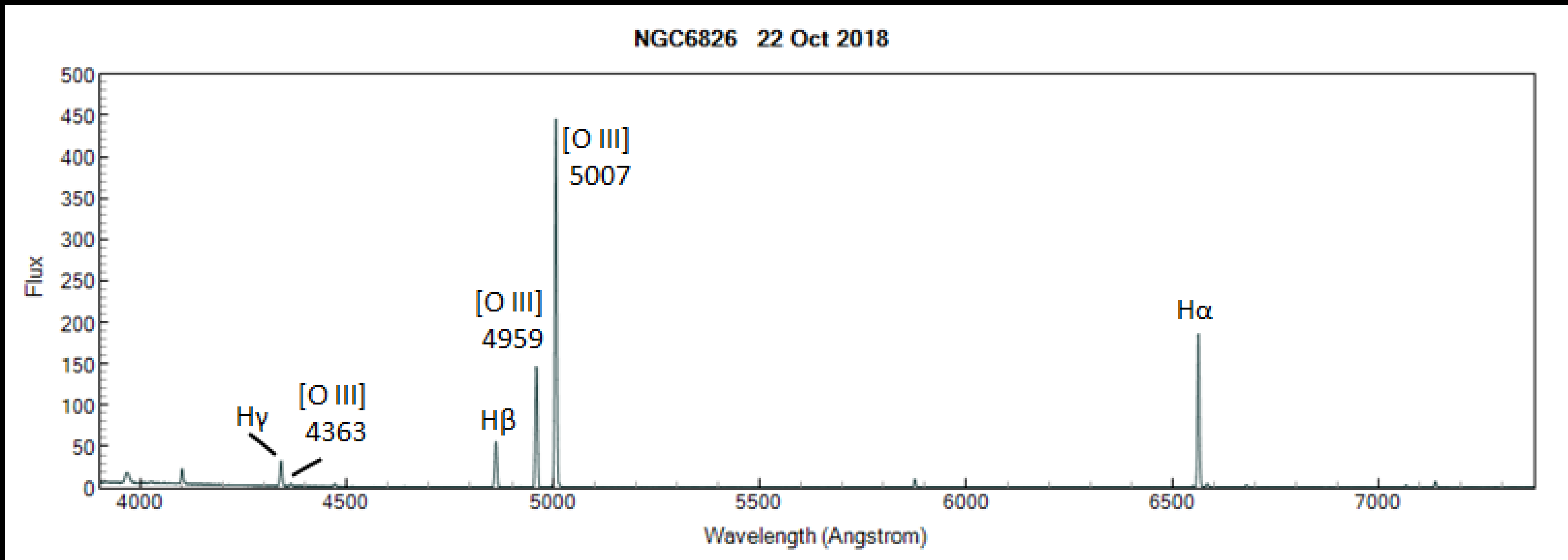
Although the EW of a line is not changed by interstellar extinction, the flux of the line is changed as the continuum changes so the measured flux ratio between lines changes.

If the flux ratio between lines is known theoretically, their measured ratio can be used to estimate the amount of extinction.

We can estimate $E(B-V)$ by comparing the measured flux ratio of the Balmer $H\alpha$ and $H\beta$ emission lines, the so-called Balmer decrement, in the rarefied atmospheres of planetary nebulae or HII regions with their theoretical values.

The flux ratios in these and other lines can also be used to estimate the electron density and electron temperature in these nebulae.

Determining interstellar extinction (6)



Hα = 1199 flux units

Hβ = 385.7 flux units

Ratio Hα/Hβ = 3.12 (theoretical value with no extinction = 2.86)

Extinction constant c(Hβ) = 3.08 * $\log_{10}$(Hα/Hβ) – 1.39 = 0.132

E(B-V) = c(Hβ) / 1.46 = 0.090

A_V = 0.29 (assuming R_V=3.1) (NED value = 0.30)

R [O III] = ([O III] 4959 + [O III] 5007) / [O III] 4363 = 225.3

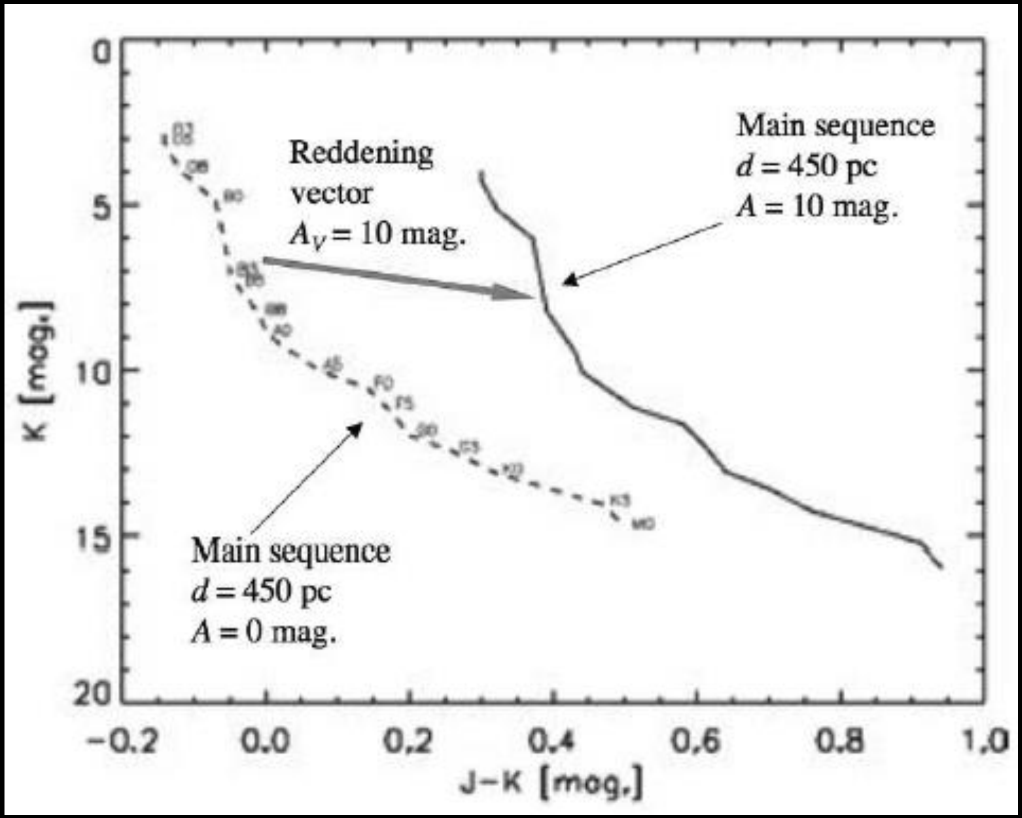
Electron temperature Te = 32900 / ln(R [O III] / 8.32) = 9973K

Zhang et al., MNRAS, 351, 935 (2004) gives a mean value of 9975K

Determining interstellar extinction (7)

Reddening can be estimated from the colour-colour diagram of a population of stars, by comparing it to the locus of unreddened main sequence stars.

This colour-colour diagram of a dust-obscured young open cluster shows it has experienced total extinction of $A_V = 10$



The workshop will cover the following topics:

1) Producing an exo-atmospheric relative flux spectrum

- processing raw spectral images
- wavelength calibration
- correcting instrumental and atmospheric losses
- rectification and normalisation
- estimating SNR
- measuring equivalent width of spectral lines

2) Calibrating the spectrum in absolute flux

- how absolute flux is measured
- how to calibrate spectra in absolute flux
- measuring absorption and emission line flux
- synthetic photometry - determining magnitudes from spectra

3) Correcting for interstellar extinction and reddening

- calculating and correcting for extinction and reddening
- determining interstellar extinction
- calculating stellar spectral energy distribution and luminosity

Calculating the photospheric SED (1)

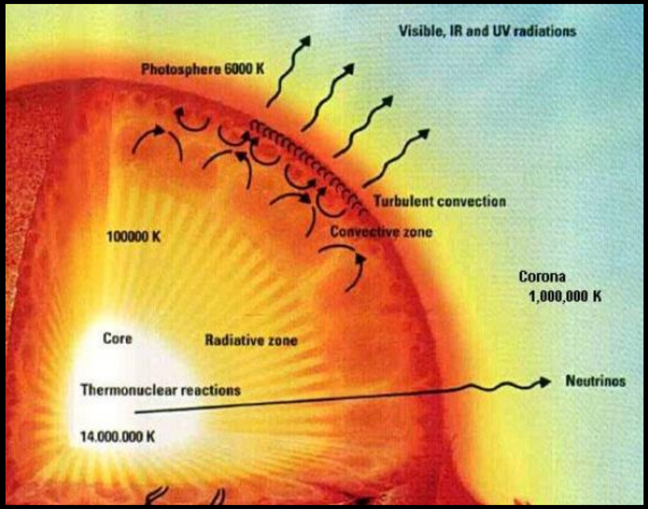
We now have a spectral energy distribution (SED) for the star which has been corrected for all losses except attenuation of flux due to the star's distance.

The star's magnitude is dimmed by the distance modulus

$$5*\log_{10}(d/10)$$

where d is the distance of the star in parsecs.

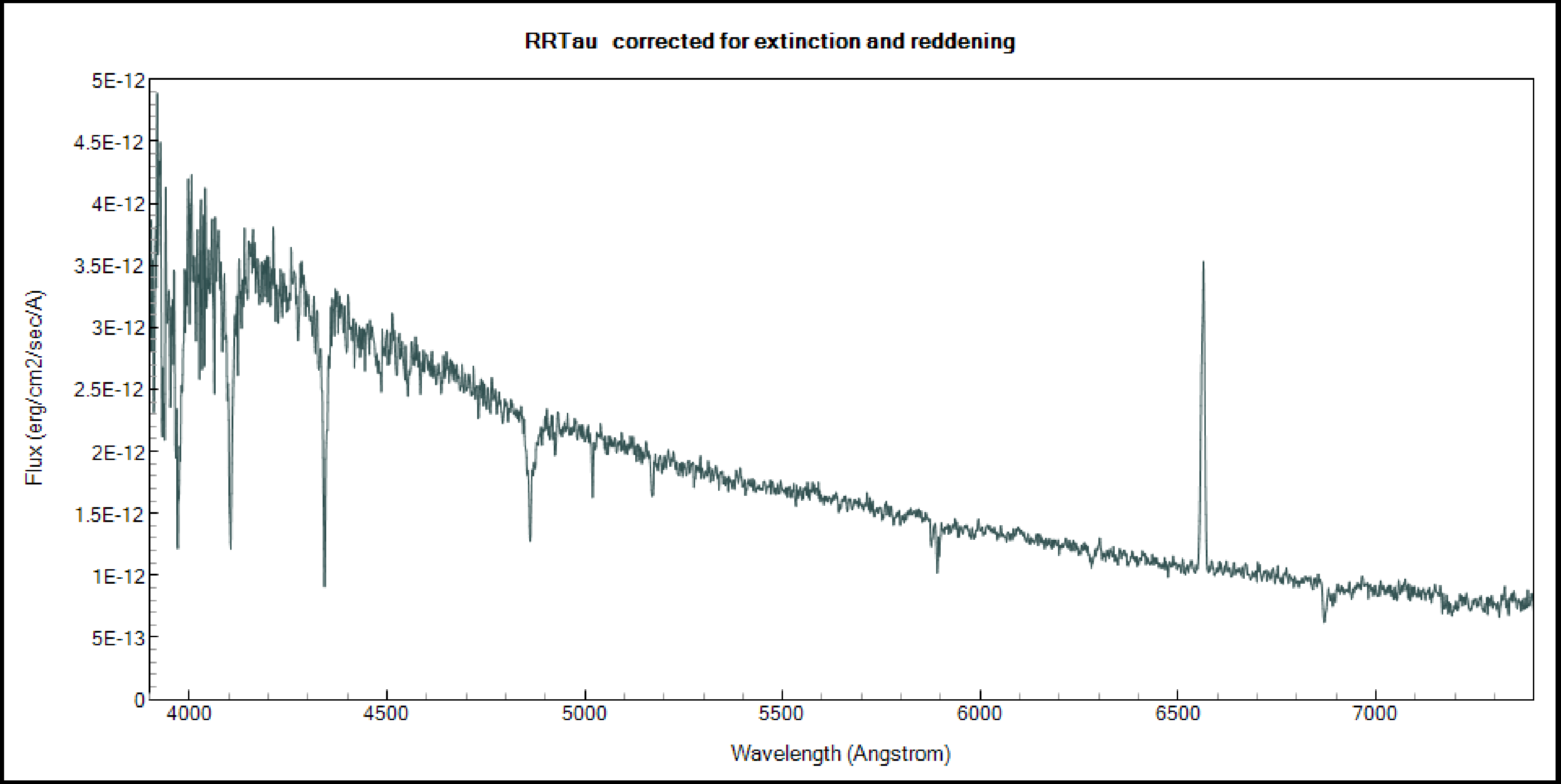
This corresponds to a reduction in flux by a factor $(d/10)^2$



Upscaling the SED by this factor finally gives us the spectral energy distribution actually emitted by the stellar photosphere.

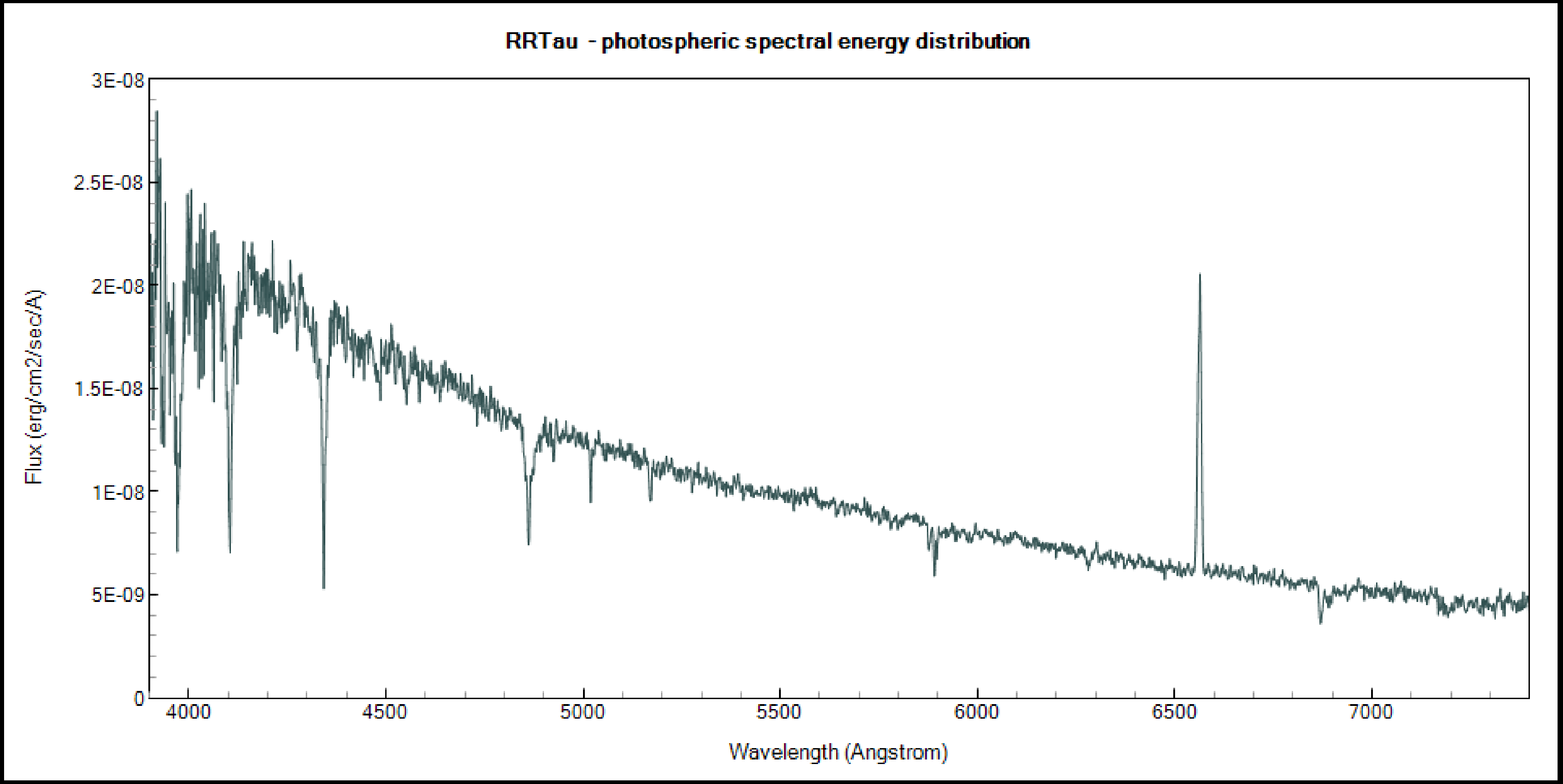
Calculating the photospheric SED (2)

Let’s look at RR Tau again. . .



Calculating the photospheric SED (3)

Its distance d = 763 pc so we have to scale its SED by $(76.3)^2 = 5282$ to find the original photospheric SED.



Calculating absolute magnitude (1)

We can use synthetic photometry with this SED to find its absolute V magnitude.

Multiply the SED by the V filter profile.
Flux transmitted by the V filter = $9.449*10^{-6}$ erg/cm^2/s
As before ZP = 13.63
Absolute magnitude $M_V = -2.5 * \log_{10}(\text{V flux}) – ZP = -1.07$

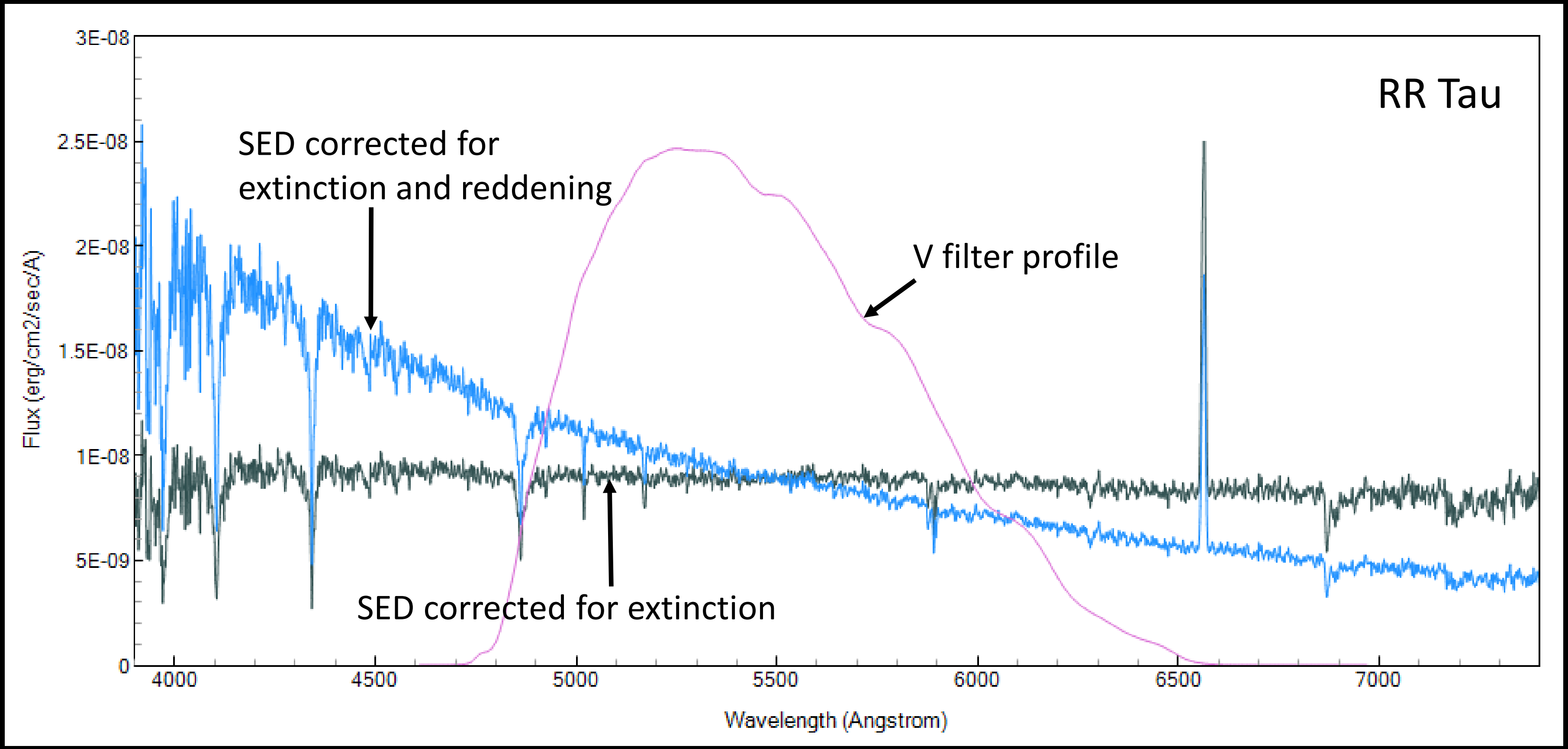
We can check this using the well-known formula including the extinction loss A_V

$$M_V = m_V – A_V – 5*\log_{10}(d/10)$$

For RR Tau we know $m_V = 11.30$, $A_V = 2.92$ and d = 763 pc
This gives $M_V = -1.03$

Close – but why are they different and which value is correct?

Calculating absolute magnitude (2)



Vflux of SED corrected for extinction = $9.140*10^{-6}$ erg/cm^2/s => $M_V = -1.03$

Vflux of SED corrected for extinction <u>and reddening</u>

= $9.449*10^{-6}$ erg/cm^2/s => $M_V = -1.07$

The value calculated from dereddened stellar flux is more accurate as it allows for reddening slightly increasing the derived absolute V magnitude.

Calculating stellar luminosity (1)

Let's assume that by one means or another we can find a star's absolute V band magnitude M_V.

A star's bolometric magnitude M_{bol} is a measure of its total energy output at all wavelengths.

This is given by $M_{bol} = M_V + BC_V$

If we know the spectral type and class of the star we can often find its V band bolometric correction BC_V in the literature or databases.

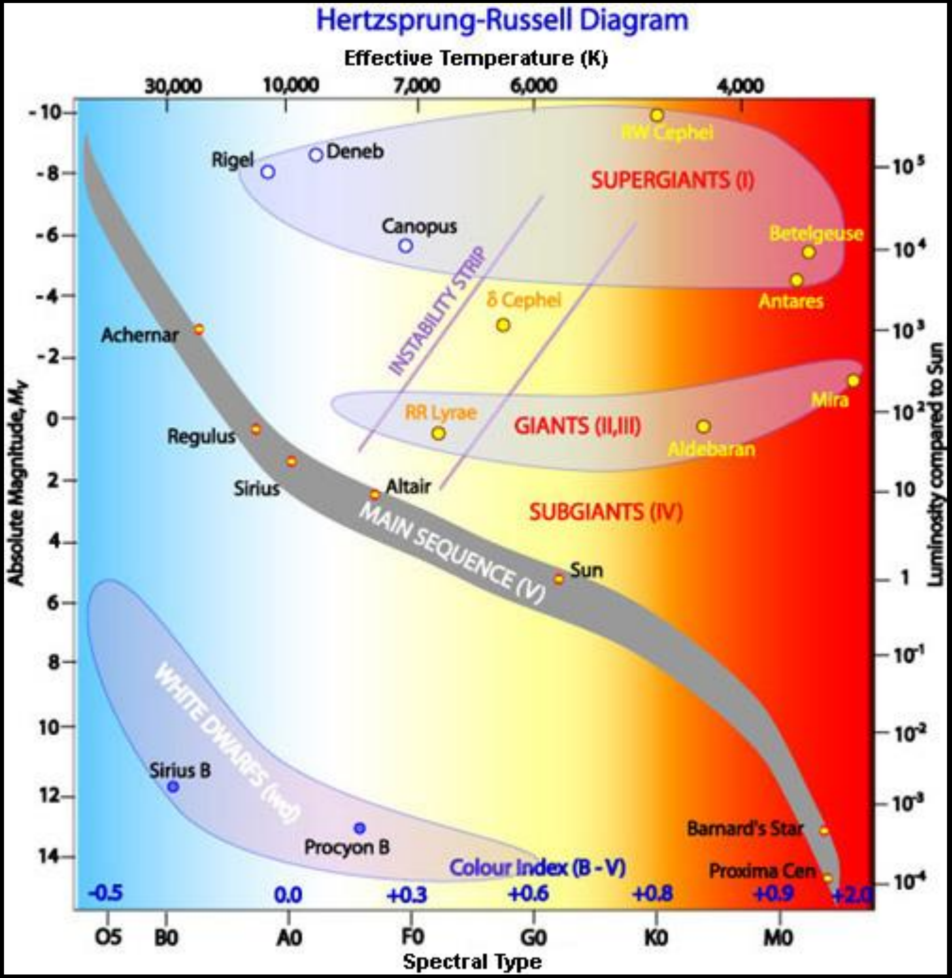
A possible source is
E. E. Mamajek, A Modern Mean Dwarf Stellar Color and Effective Temperature Sequence
http://iopscience.iop.org/article/10.1088/0067-0049/208/1/9/pdf
http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

Calculating stellar luminosity (2)

Knowing the bolometric magnitude we can find the absolute luminosity of the star relative to the Sun $L/L_{\odot}$ from

$\log_{10}(L/L_{\odot}) = -0.4 * (M_{bol} - 4.75)$

Knowing the star's spectral type and its absolute luminosity, we can locate it in the Hertzsprung-Russell diagram and determine its spectral class (dwarf, giant, supergiant).



In conclusion

We have now arrived at our final objective
– a fully corrected spectral energy distribution of the light
as it was omitted by the star we are interested in . . . .

Photon's perilous journey from stellar photosphere to pixel