Observing with a LISA spectrograph

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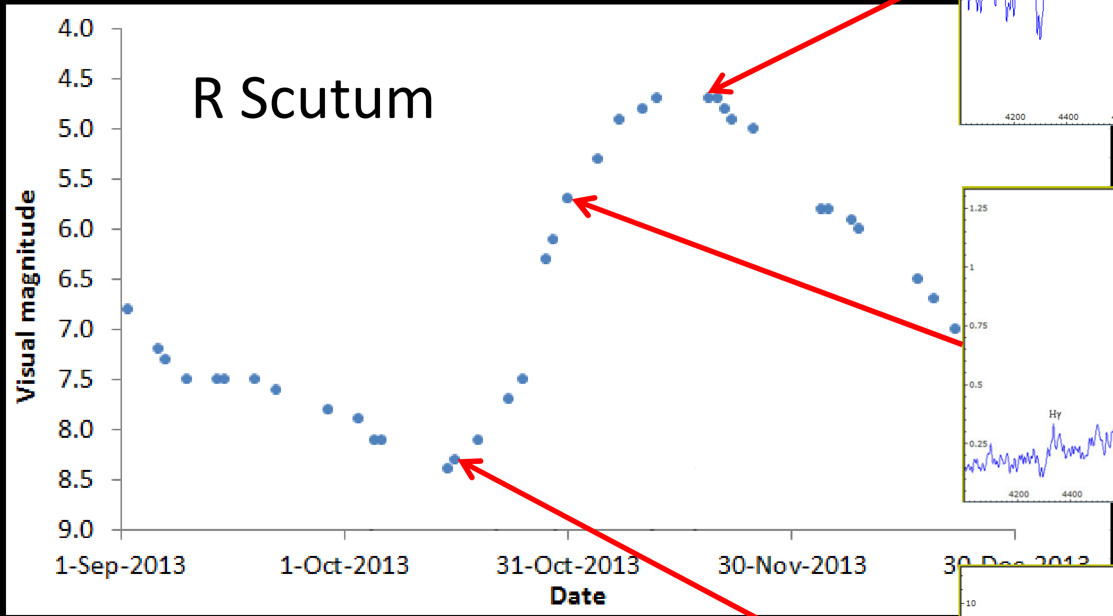
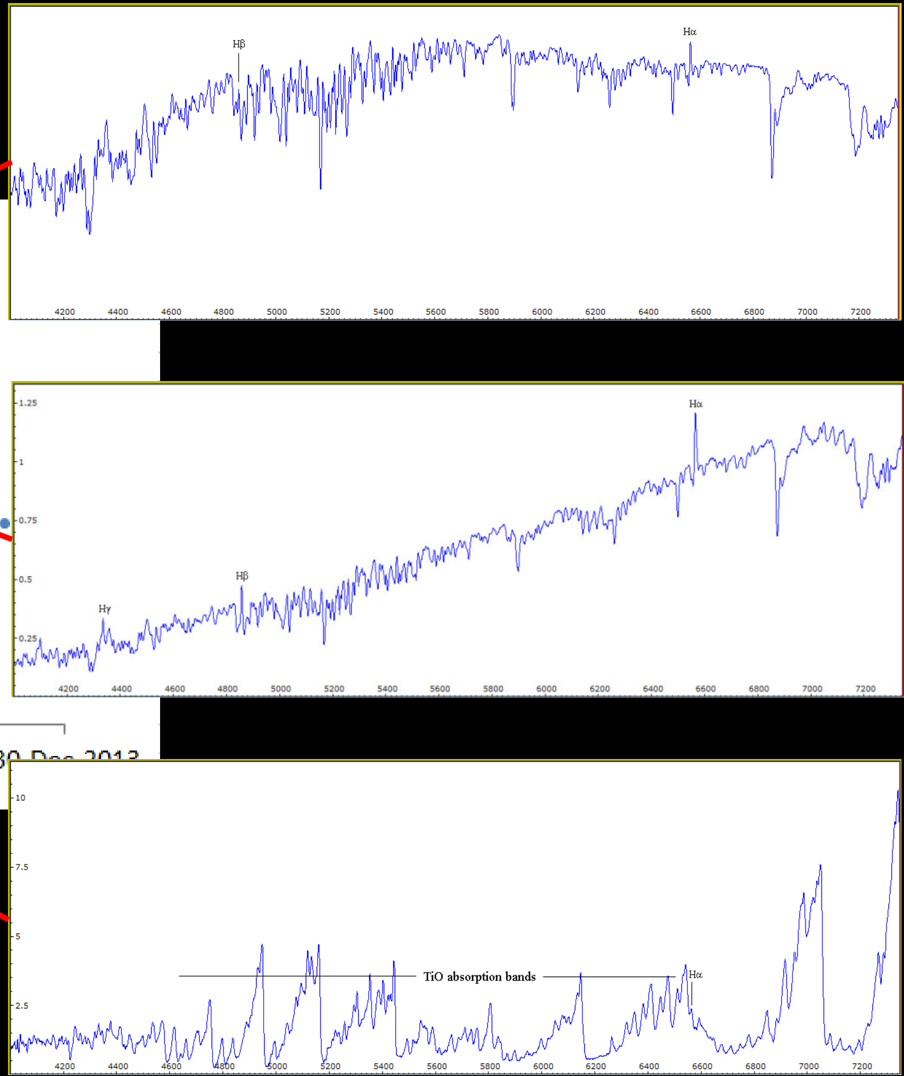
BAAVSS, AAVSO, CBA

For me, the appeal of spectroscopy is in its scientific potential

Photometry reveals changes in a star's brightness





Spectroscopy reveals why these changes are happening

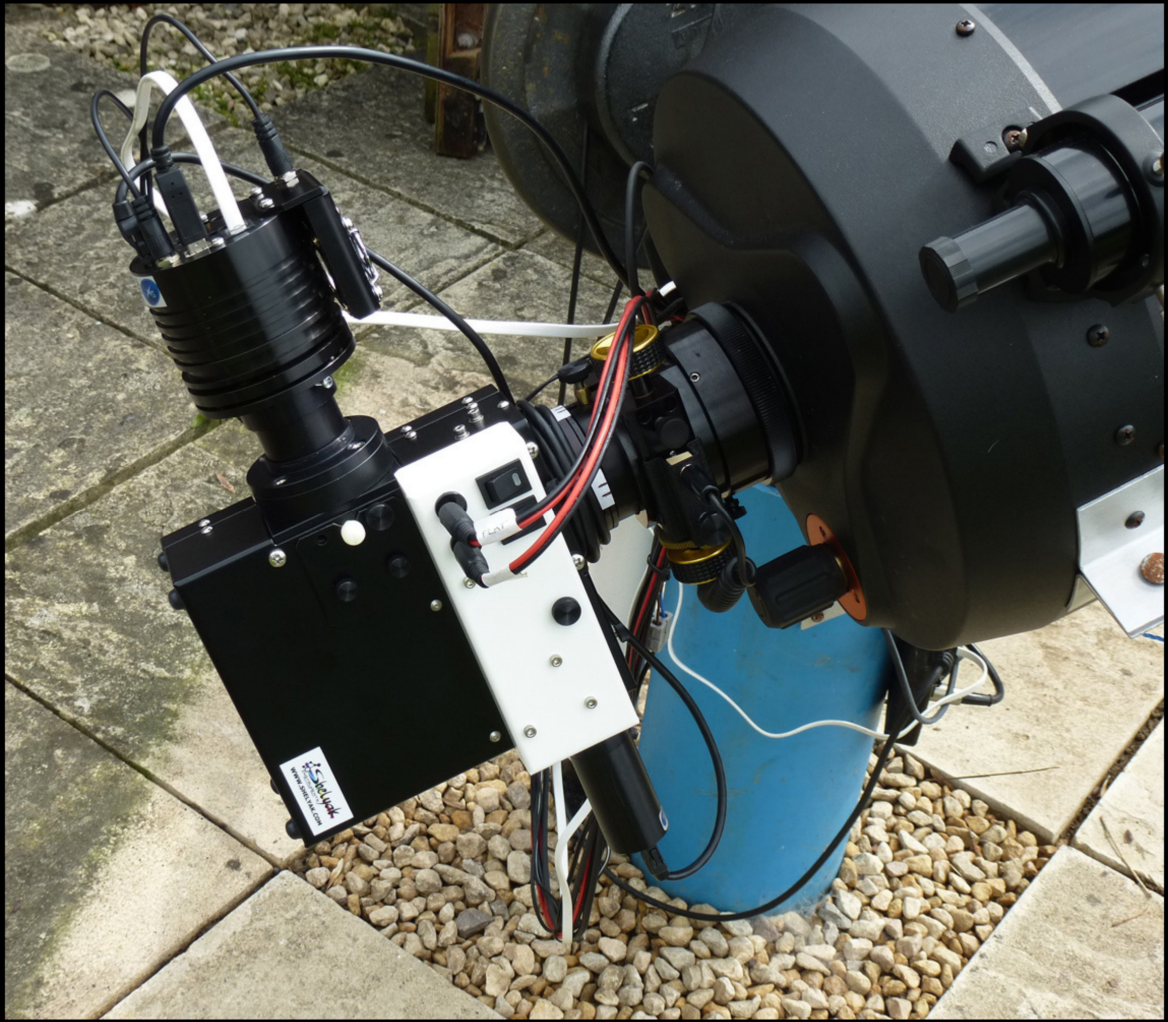
My aim is to get as close as possible to the spectral flux or energy distribution with wavelength emitted by the target object

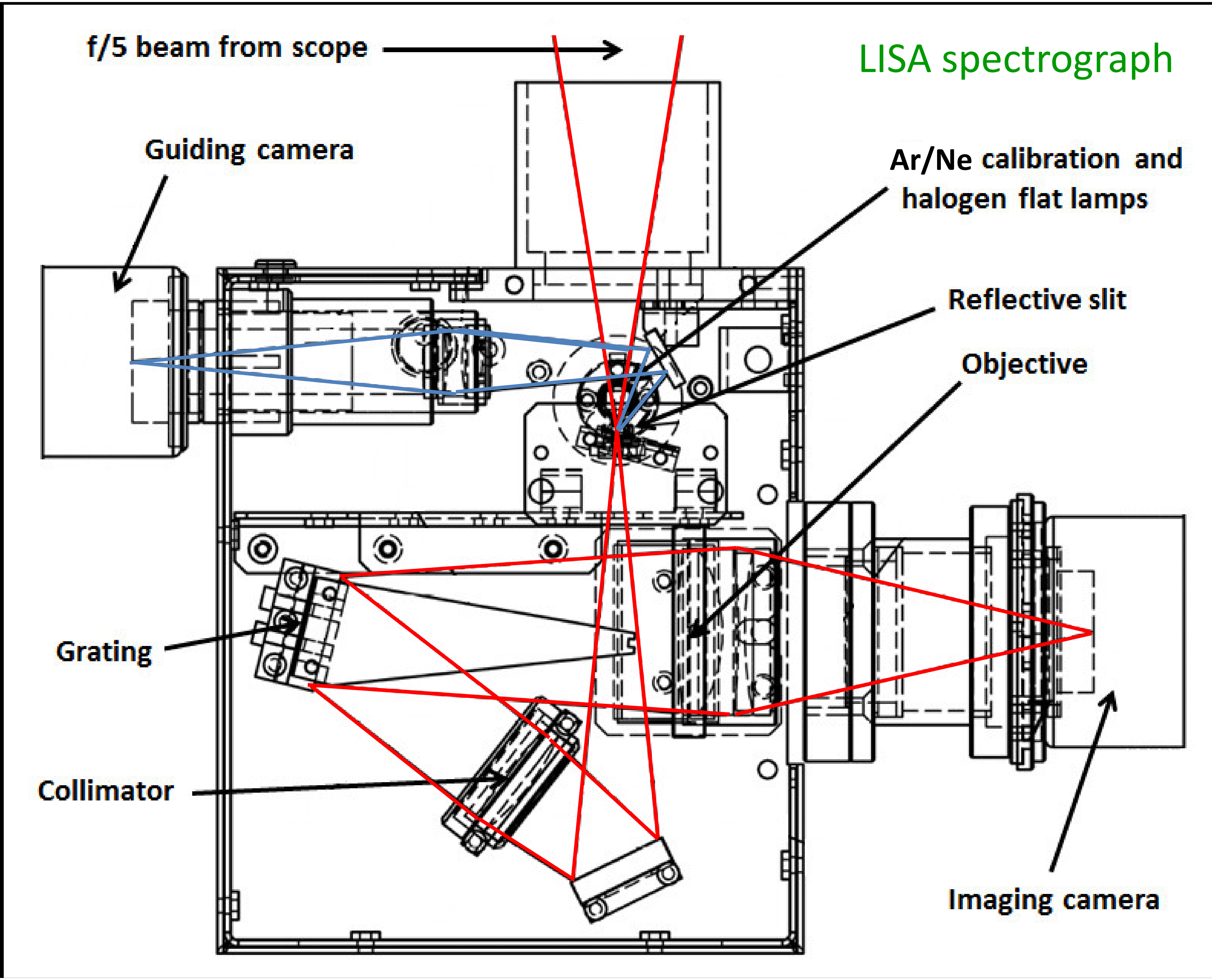
To do this I need to:

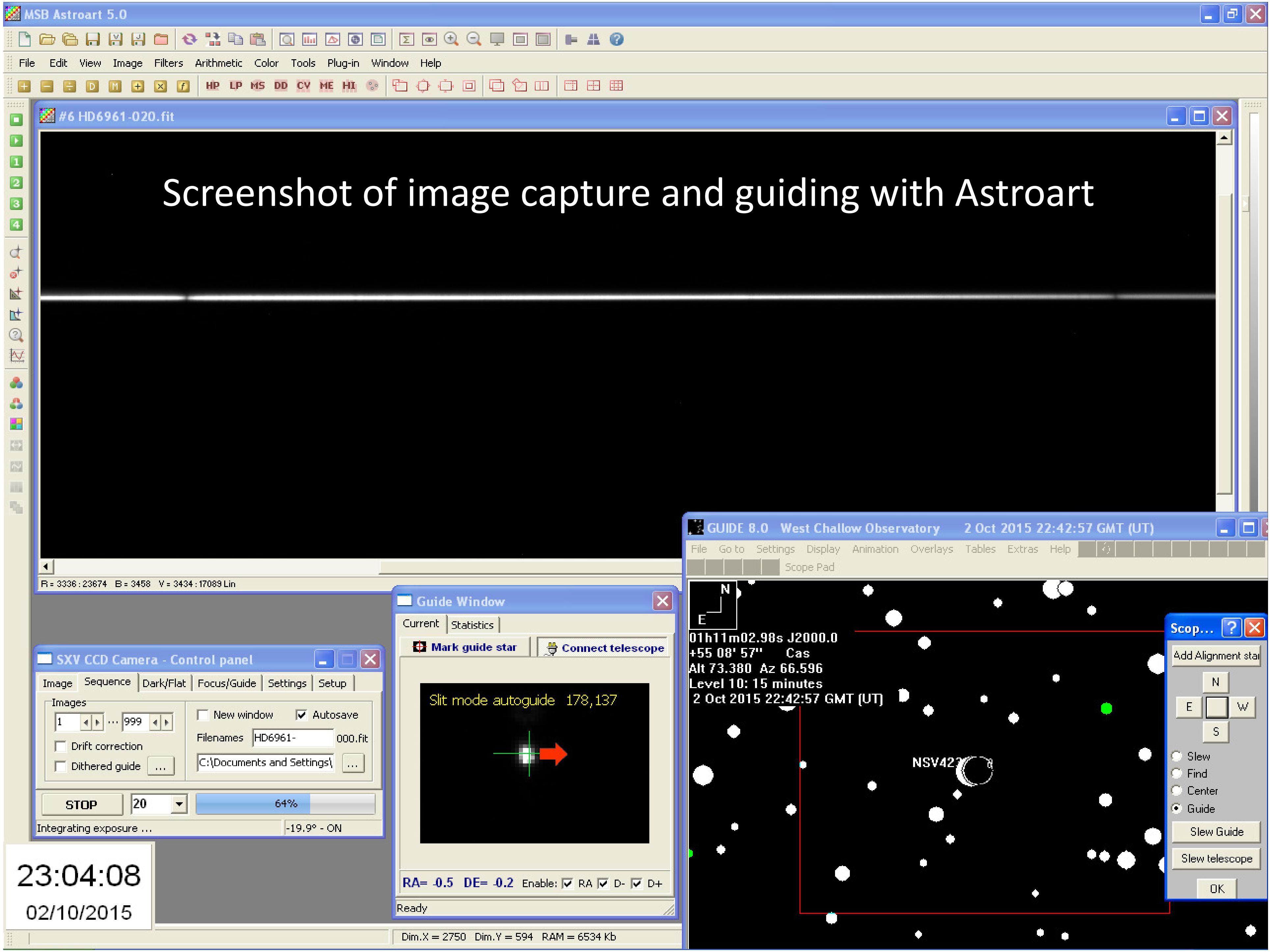
- Calibrate pixel to wavelength transformation for the instrument
- Correct for instrument and atmospheric responses
- Convert the spectrum onto an absolute flux scale
- Correct for interstellar extinction and reddening

My setup

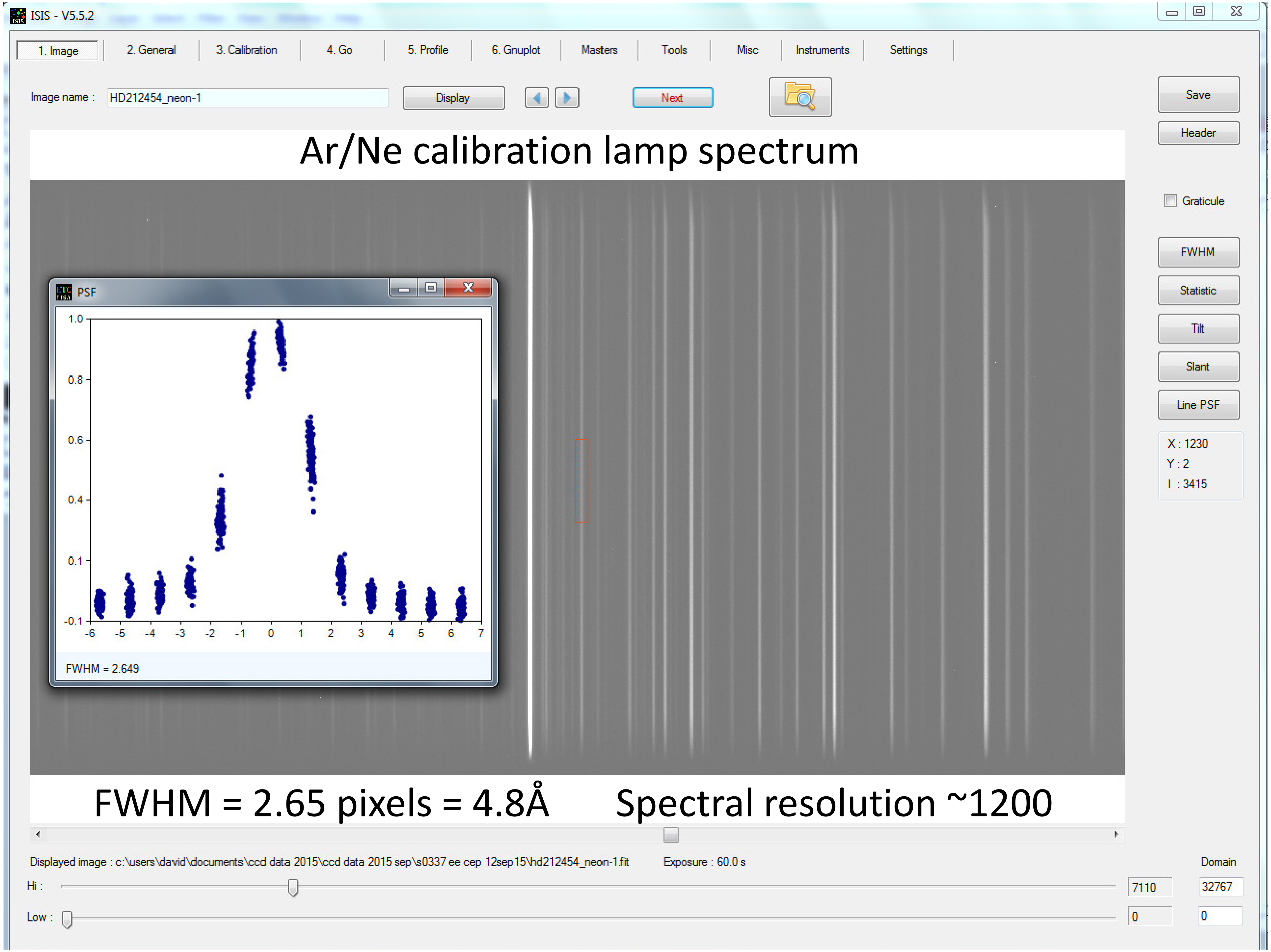
- C11 scope
- Optec 0.5x FR
- G-11 mount
- LISA spectrograph
- SXVR-H694 CCD
- SXV-EX guider
- Astroart
- Guide



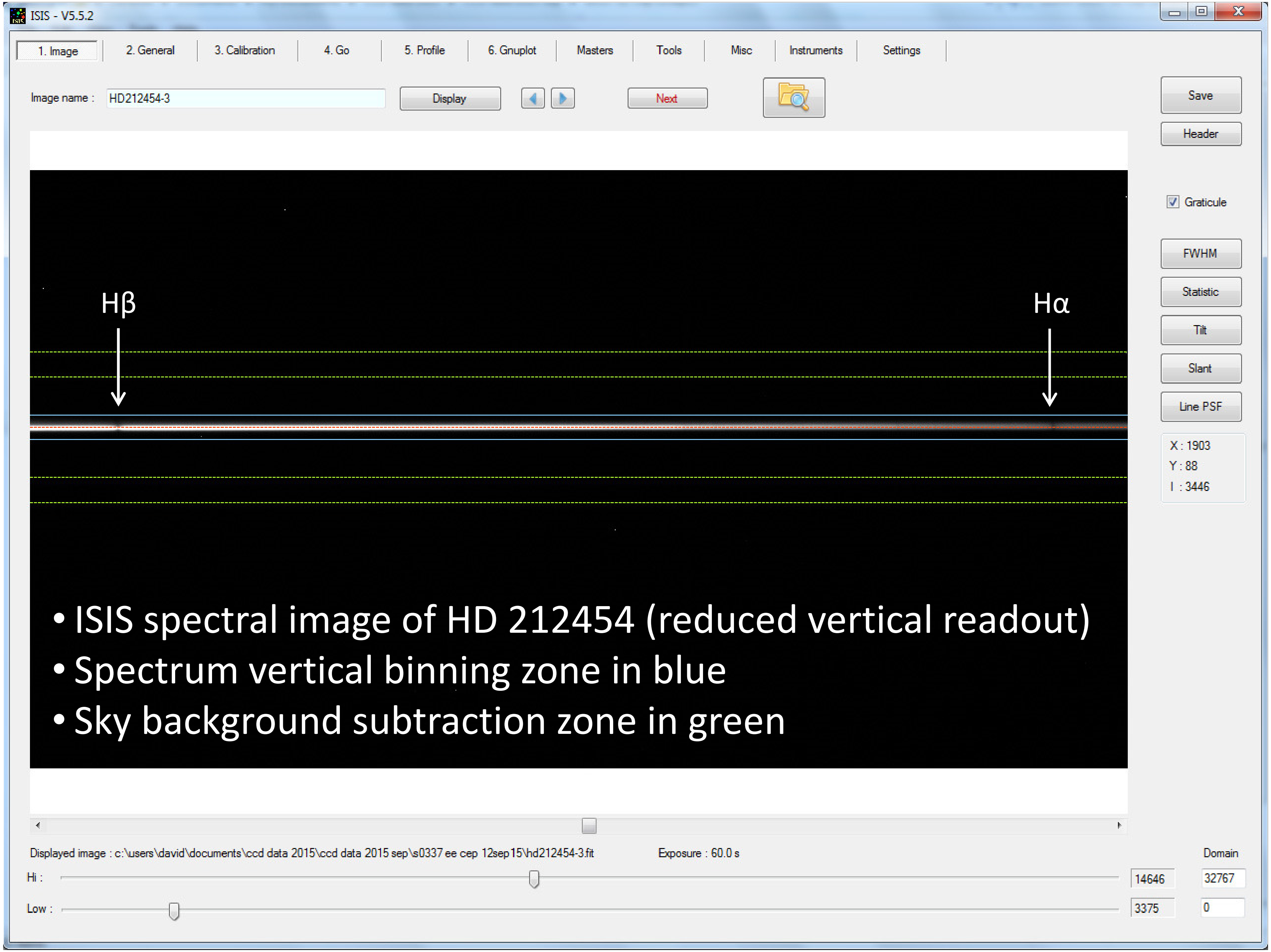

LISA spectrograph
f/5 beam from scope
Guiding camera
Ar/Ne calibration and
halogen flat lamps
Reflective slit
Objective
Grating
Collimator
Imaging camera


MSB Astroart 5.0
File Edit View Image Filters Arithmetic Color Tools Plug-in Window Help
#6 HD6961-020.fit
Screenshot of image capture and guiding with Astroart
R = 3336 : 23674 B = 3458 V = 3434 : 17089 Lin
SXV CCD Camera - Control panel
Image Sequence Dark/Flat Focus/Guide Settings Setup
Images
1 ... 999
New window
Autosave
Drift correction
Filenames HD6961- 000.fit
Dithered guide
C:\Documents and Settings\
STOP
20
64%
Integrating exposure ...
-19.9° - ON
23:04:08
02/10/2015
Guide Window
Current Statistics
Mark guide star
Connect telescope
Slit mode autoguide 178,137
RA= -0.5 DE= -0.2 Enable: RA D- D+
Ready
Dim.X = 2750 Dim.Y = 594 RAM = 6534 Kb
GUIDE 8.0 West Challow Observatory 2 Oct 2015 22:42:57 GMT (UT)
File Go to Settings Display Animation Overlays Tables Extras Help
Scope Pad
N
E
01h11m02.98s J2000.0
+55 08' 57" Cas
Alt 73.380 Az 66.596
Level 10: 15 minutes
2 Oct 2015 22:42:57 GMT (UT)
NSV42
Scop...
Add Alignment star
N
E
W
S
Slew
Find
Center
Guide
Slew Guide
Slew telescope
OK

Ar/Ne calibration lamp spectrum

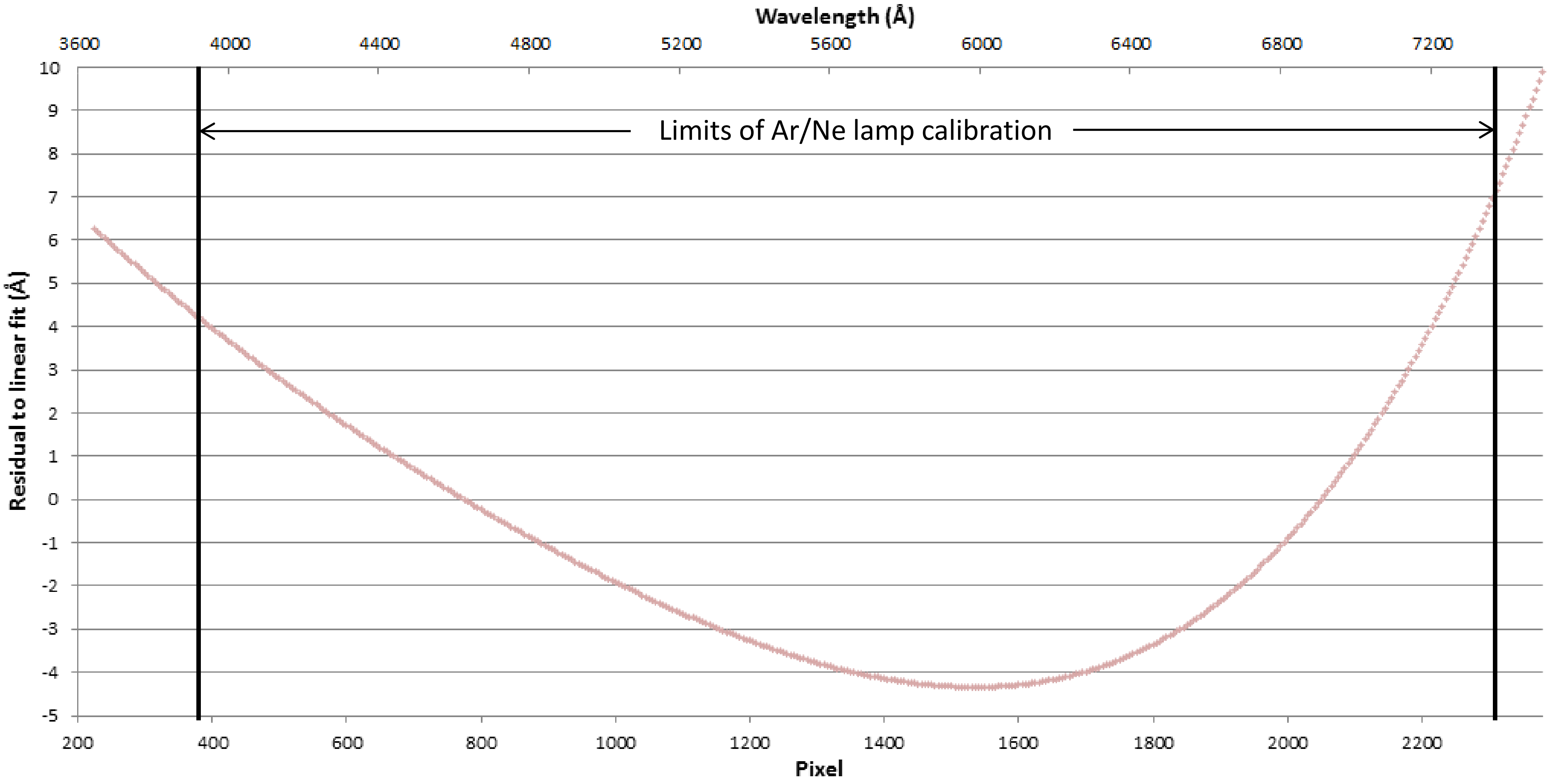


FWHM = 2.65 pixels = 4.8Å Spectral resolution ~1200


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Image name : HD212454-3
Display
Next
Save
Header
Graticule
FWHM
Statistic
Tilt
Slant
Line PSF
X : 1903
Y : 88
I : 3446
Hβ
Hα
• ISIS spectral image of HD 212454 (reduced vertical readout)
• Spectrum vertical binning zone in blue
• Sky background subtraction zone in green
Displayed image : c:\users\david\documents\ccd data 2015\ccd data 2015 sep\s0337 ee cep 12sep15\hd212454-3.fit
Exposure : 60.0 s
Domain
Hi :
14646
32767
Low :
3375
0

Wavelength calibration

4th order fit of wavelength vs pixel number – residual to linear fit



Using 16 Ar/Ne emission lines, the fit has an rms residual of ~0.1Å

Correcting for instrumental and atmospheric response

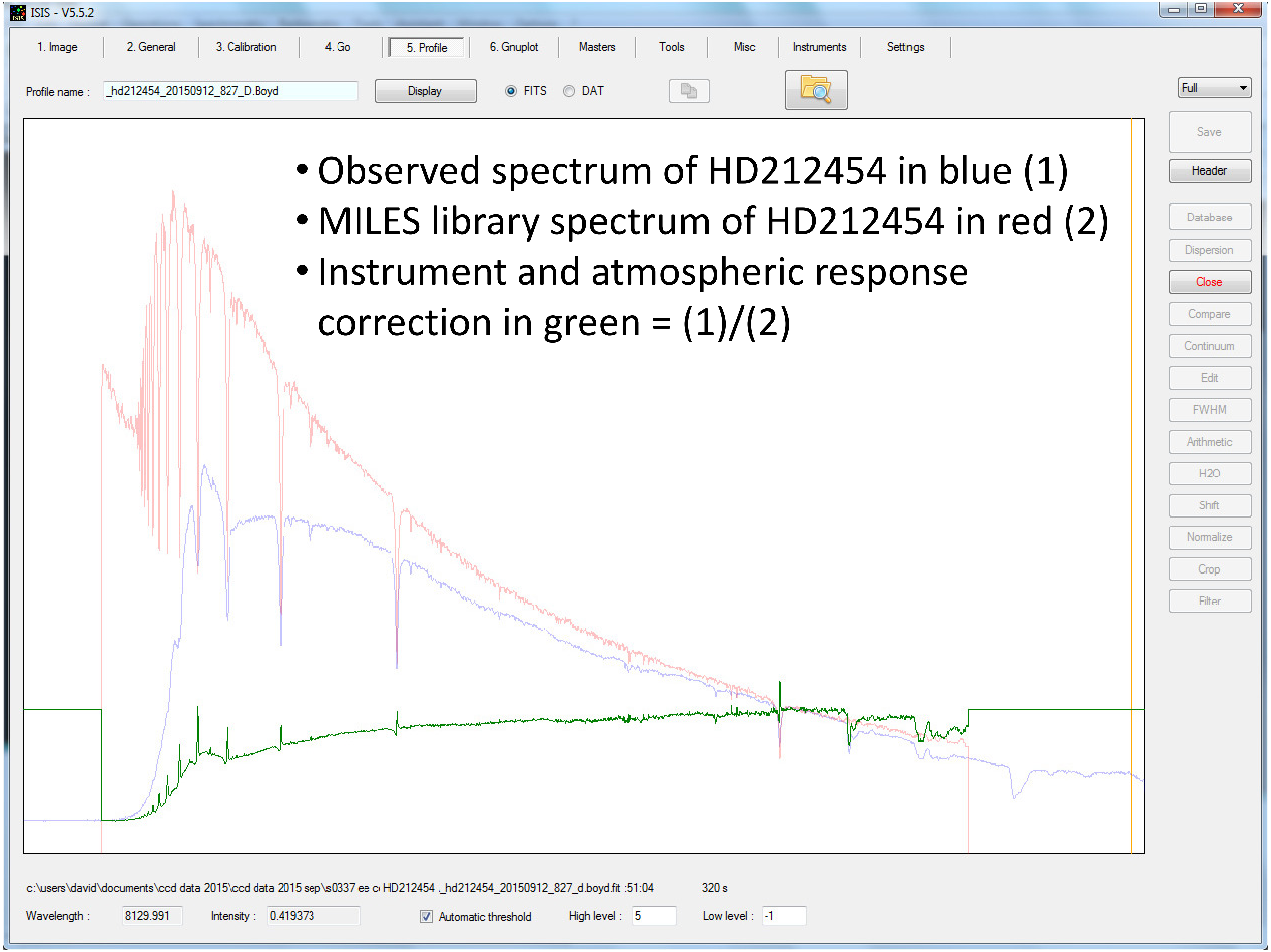
These can most easily be achieved by taking the spectrum of an A or B-type star, ideally A0V, with a known spectrum at the same altitude as the target star

A and B stars have a smooth continuum and few spectral lines

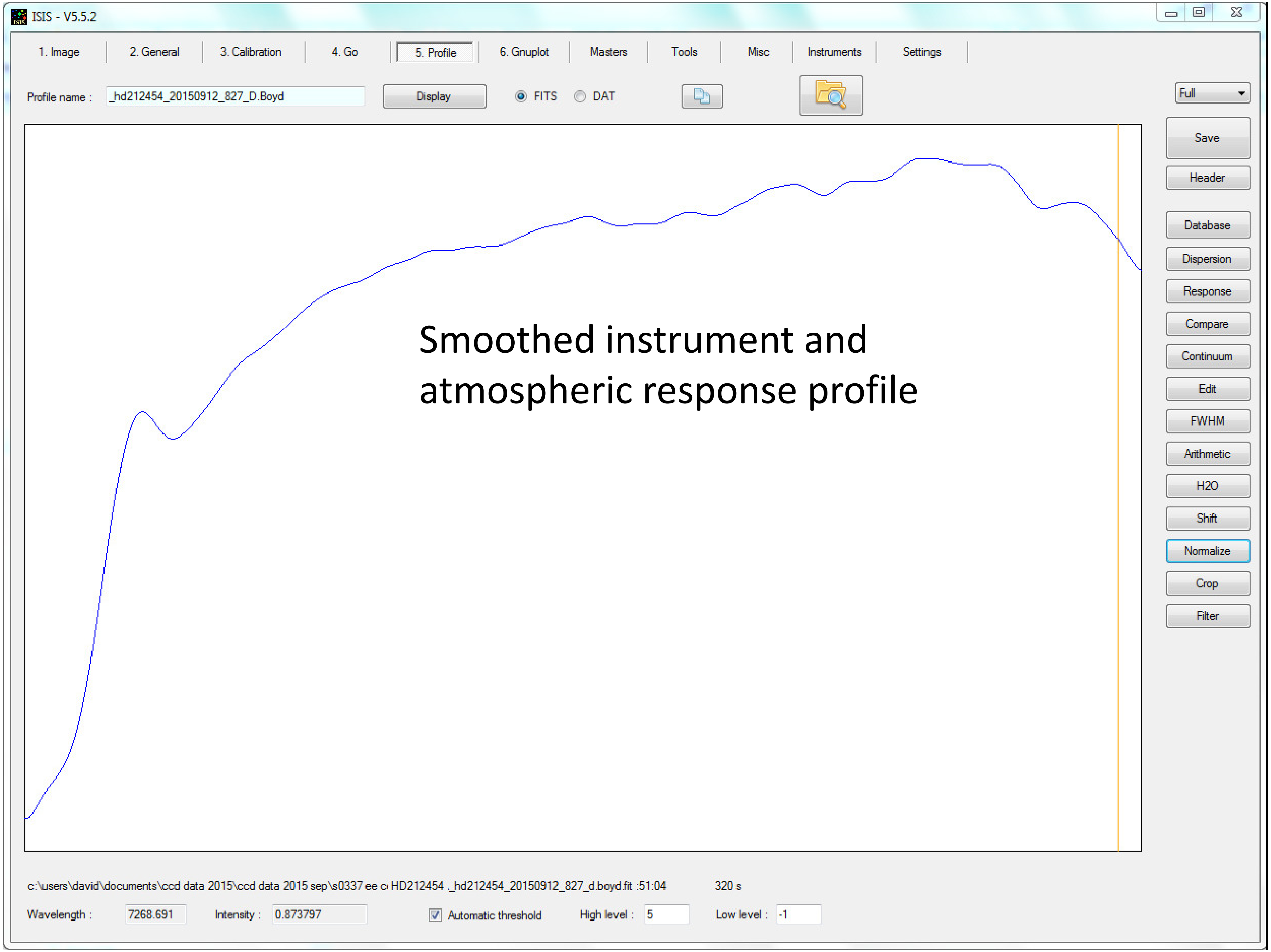
Ideally choose a star in the MILES library which has exact spectra

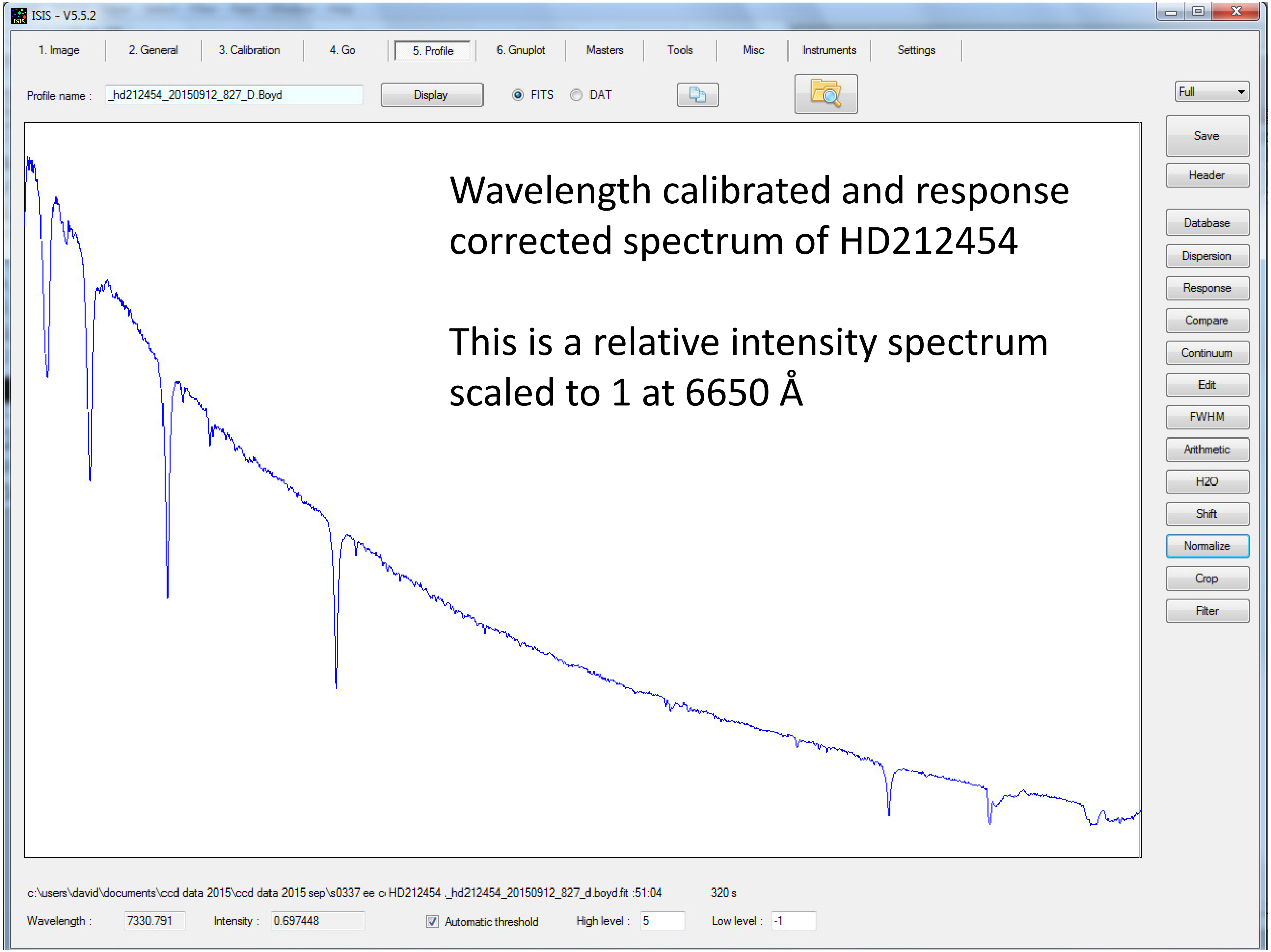
Otherwise use a generic spectrum of the correct type from the Pickles library

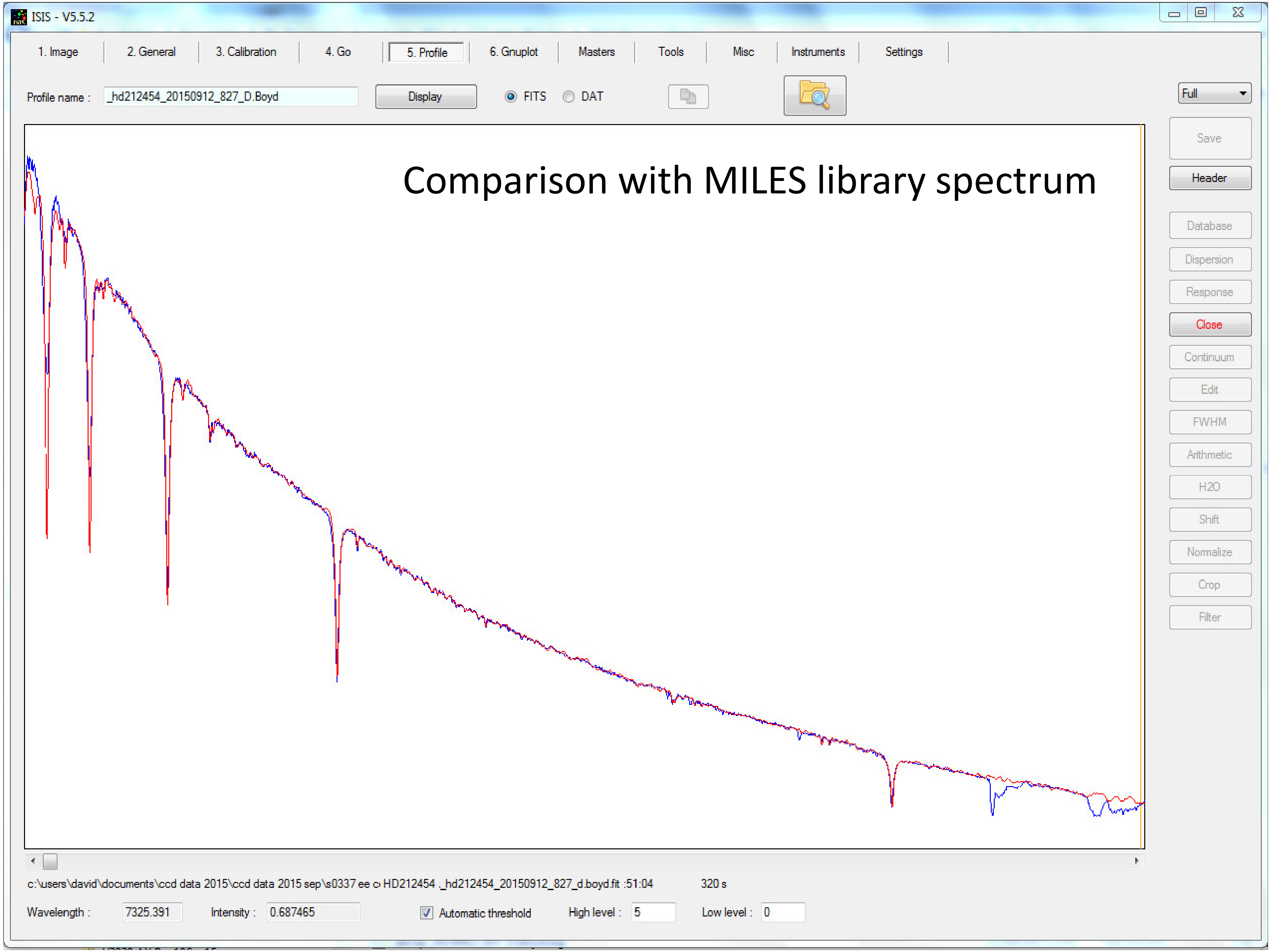
At the same altitude these stars will suffer the same atmospheric attenuation so the effects will cancel out



ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name :
_hd212454_20150912_827_D.Boyd
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Close
Compare
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
• Observed spectrum of HD212454 in blue (1)
• MILES library spectrum of HD212454 in red (2)
• Instrument and atmospheric response correction in green = (1)/(2)
c:\users\david\documents\ccd data 2015\ccd data 2015 sep\s0337 ee c HD212454 _hd212454_20150912_827_d.boyd.fit :51:04
320 s
Wavelength :
8129.991
Intensity :
0.419373
Automatic threshold
High level :
5
Low level :
-1


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name :
_hd212454_20150912_827_D.Boyd
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Compare
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Smoothed instrument and atmospheric response profile
c:\users\david\documents\ccd data 2015\ccd data 2015 sep\s0337 ee c HD212454 _hd212454_20150912_827_d.boyd.fit :51:04
320 s
Wavelength :
7268.691
Intensity :
0.873797
Automatic threshold
High level :
5
Low level :
-1


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name : _hd212454_20150912_827_D.Boyd
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Compare
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Wavelength calibrated and response corrected spectrum of HD212454
This is a relative intensity spectrum scaled to 1 at 6650 Å
c:\users\david\documents\ccd data 2015\ccd data 2015 sep\s0337 ee ci HD212454 _hd212454_20150912_827_d.boyd.fit :51:04
320 s
Wavelength : 7330.791
Intensity : 0.697448
Automatic threshold
High level : 5
Low level : -1


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name :
_hd212454_20150912_827_D.Boyd
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Close
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Comparison with MILES library spectrum
c:\users\david\documents\ccd data 2015\ccd data 2015 sep\s0337 ee c HD212454 _hd212454_20150912_827_d.boyd.fit :51:04
320 s
Wavelength :
7325.391
Intensity :
0.687465
Automatic threshold
High level :
5
Low level :
0

Why flux calibrate?

If a relative intensity spectrum is sufficient, eg to identify what spectral lines are present, there is no need to flux calibrate

But a relative intensity spectrum contains no information about the absolute level of flux or energy density of the spectrum

So it is impossible to monitor changes in the energy output of a star over time or to detect changes in the energy distribution across the spectrum

Flux calibration brings spectra onto an absolute flux scale in units of erg/cm^2/sec/Å

Flux calibration

There are 2 methods of flux calibration generally used by amateurs

- Wide slit method described by Christian Buil

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

- Calculation based on a simultaneously measured V magnitude

  (based on work of Martin Dubs, Francois Teyssier, Robin Leadbeater and others)

Given the limited time, I will only talk about the latter method which I have used successfully

The principle is simple….

- You measure the absolute flux of the object transmitted through a V filter and compare that with the flux through the same V filter from a relative flux spectrum
- You then scale the relative flux spectrum by the ratio of these two numbers to get an absolute flux spectrum
- To find the absolute flux transmitted by a V filter, you need to know the spectroscopic zero point for your V filter
- For this you need spectra of some spectrophotometric standard stars – these are available in the CALSPEC library

Calculating the V filter zero point

Let $F_s(\lambda)$ be the absolute spectral flux density from a spectrophotometric standard star

Let $R(\lambda)$ be the spectral transmission profile of our V filter

Then the absolute flux transmitted by the V filter is

$$\int R(\lambda)\, F_s(\lambda)\, d\lambda$$

The measured V magnitude of the standard star is given by

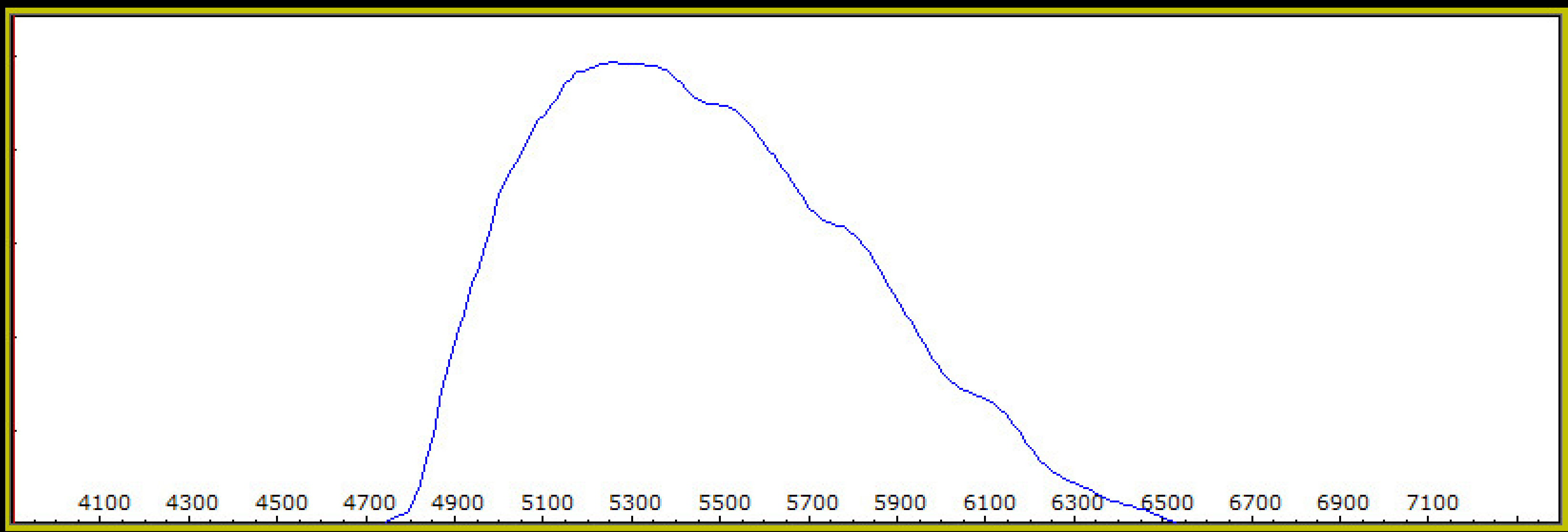
$$m_s = -2.5 \log_{10} [\int R(\lambda)\, F_s(\lambda)\, d\lambda\ ] - ZP$$

where ZP is a zero point

So $$ZP = -m_s - 2.5 \log_{10} [\int R(\lambda)\, F_s(\lambda)\, d\lambda\ ]$$

By measuring $\int R(\lambda)\, F_s(\lambda)\, d\lambda$ for a set of standard stars with known absolute spectral flux density profiles and V magnitudes, we can determine the zero point for our V filter

To do this we need to know $R(\lambda)$, the spectral transmission profile of our V filter



This is the profile of the Astrodon V filter which I use

ID	Sp type	V mag	Flux transmitted	Zero point
Vega	A0V	0.03	3.4580E-06	13.62
BD+75_325	O5p	9.55	5.4967E-10	13.60
HD93521	O9Vp	6.99	5.6932E-09	13.62
HZ44	sdO	11.67	7.7100E-11	13.61
BD+33_2642	B2IV	10.83	1.6718E-10	13.61
HD1732526	A4V	12.53	3.4390E-11	13.63
HD1740346	A6V	12.48	3.5439E-11	13.65
HD1743045	A8III	13.52	1.3698E-11	13.64
HD1802271	A2V	11.98	5.6297E-11	13.64
HD1805292	A4V	12.28	4.2837E-11	13.64
HD1812095	A5V	11.74	7.0920E-11	13.63
BD+28_4211	Op	10.51	2.2346E-10	13.62
G93-48	DA3	12.74	2.8068E-11	13.64
HD209458	G0V	7.65	3.0378E-09	13.64
BD+17_4708	sfF8	9.47	5.6767E-10	13.64
FEIGE110	D0p	11.83	6.5565E-11	13.63
			Mean	13.630
			Std dev	0.014

Flux is in erg/cm^2/sec/Å

ZP = - V mag - 2.5 log(flux)

← spectroscopic zero point ZP (Mean)

Converting a relative flux spectrum to absolute flux

Suppose $F_t(\lambda)$ is the absolute spectral flux density from our target star (this is what we want to know)

The measured V magnitude of the target star is given by

$$m_t = -2.5 \log_{10} [\int R(\lambda) F_t(\lambda) d\lambda] - ZP$$

The absolute flux from the target star transmitted by the V filter is

$$F_A = \int R(\lambda) F_t(\lambda) d\lambda = 10 \wedge [-0.4 * (m_t + ZP)]$$

If $f_t(\lambda)$ is the relative spectral flux density of our target star (what we measure) then the relative flux transmitted by the V filter is

$$F_R = \int R(\lambda) f_t (\lambda) d\lambda$$

We can then find the absolute spectral flux density $F_t(\lambda)$ by scaling the relative flux density $f_t(\lambda)$ by F_A / F_R

Worked example: CALSPEC star BD+25 4655 (B0)

- We know $m_t = 9.68$

- So we know the absolute flux transmitted by the V filter is

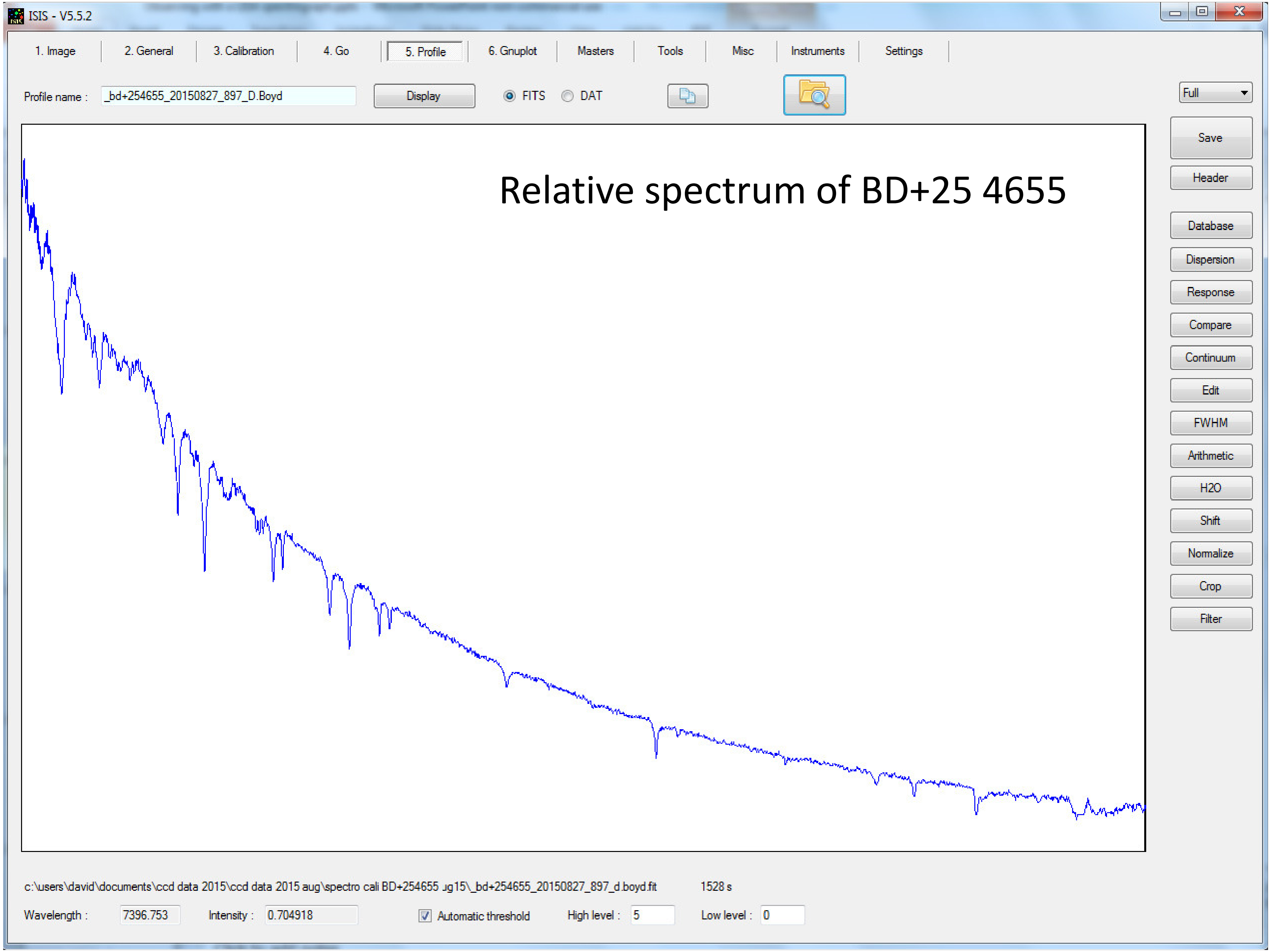
  $F_A = 10 \wedge [-0.4 * (9.68 + 13.63)] = 4.7424*10^{-10}$ erg/cm^2/sec/Å

- Take a relative flux spectrum of BD+25 4655, multiply it by the V filter profile and measure the relative flux transmitted by the V filter

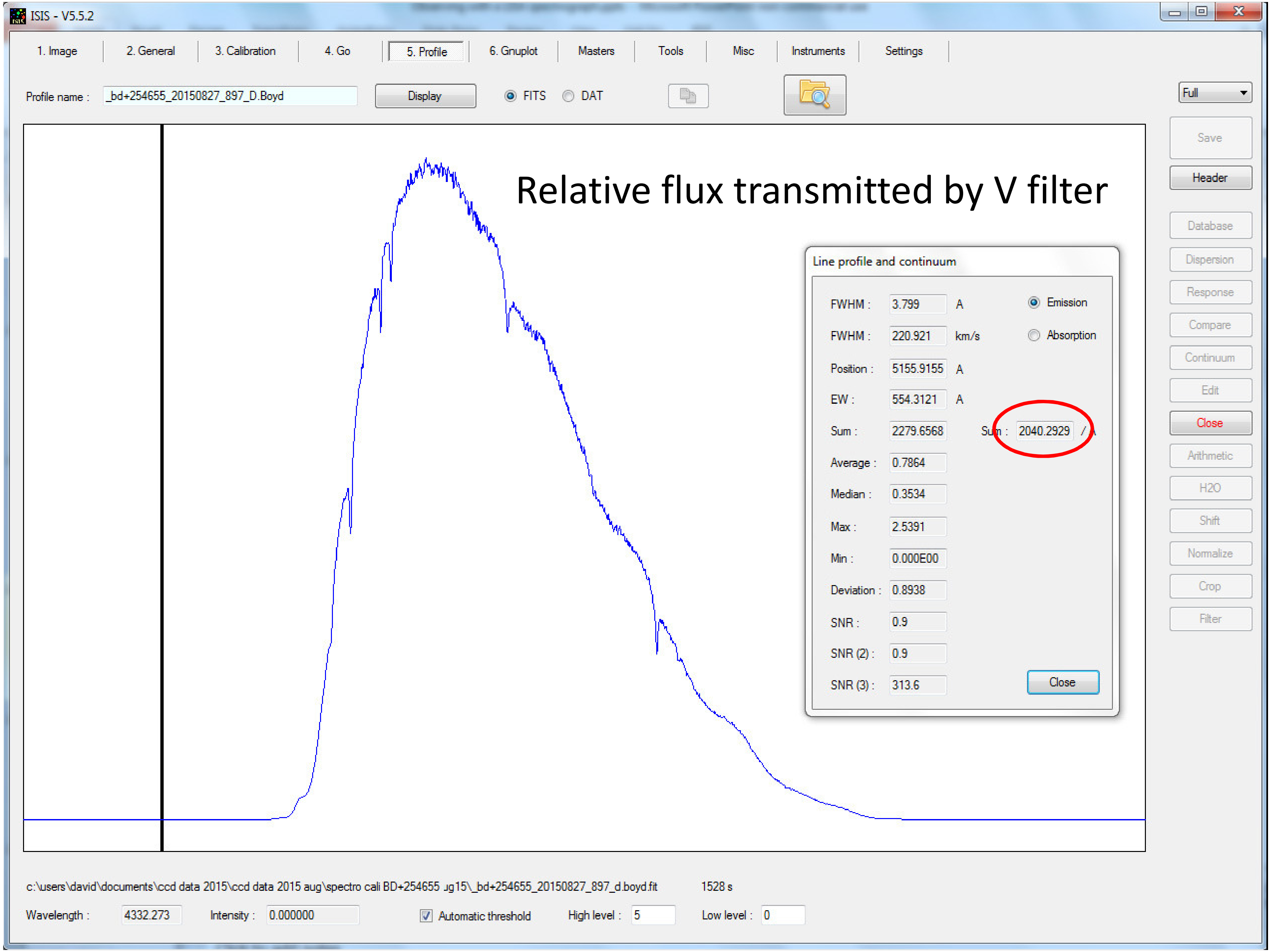
  $F_R = 2040.2929$

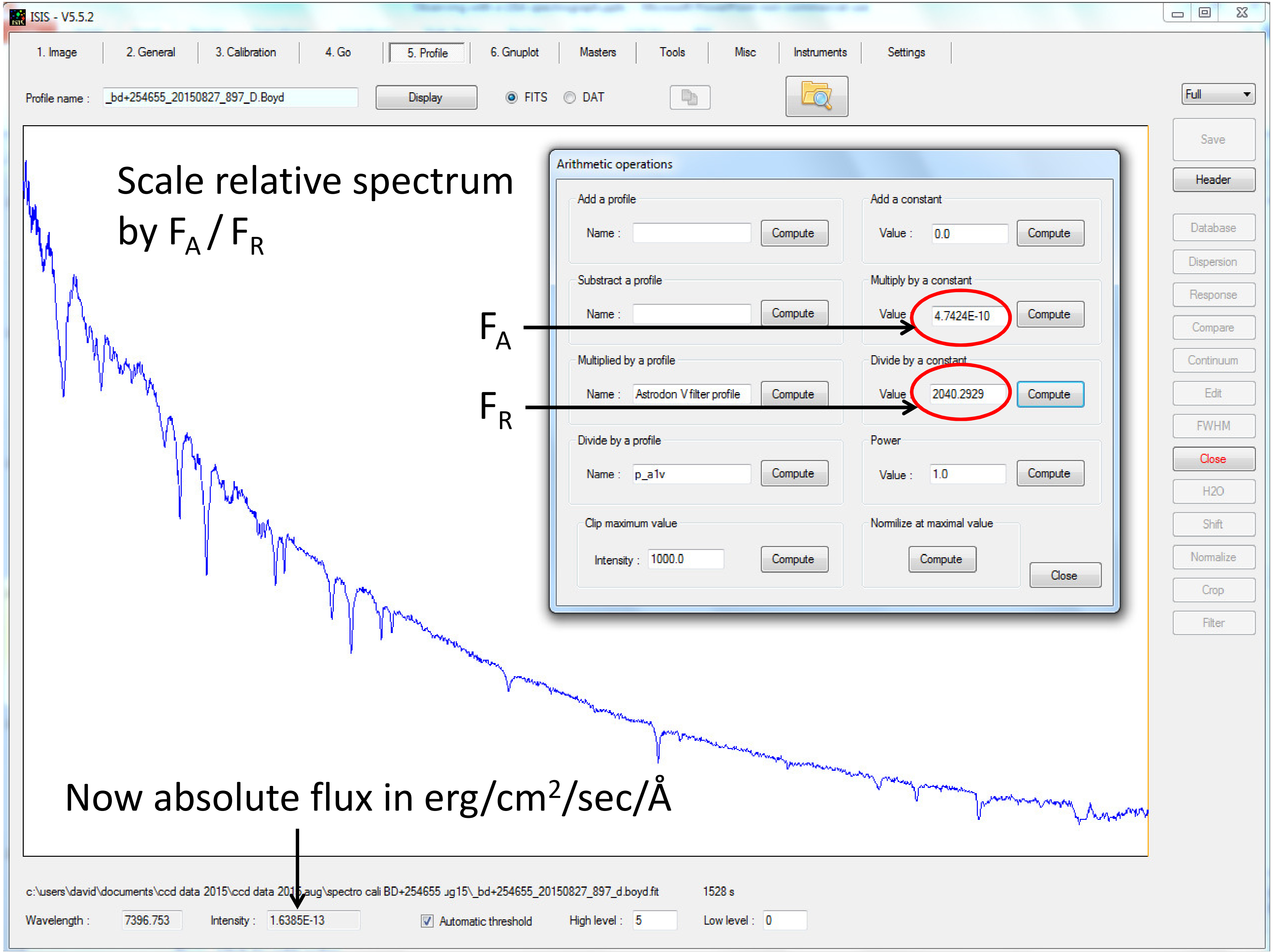
- To get the absolute flux spectrum of BD+25 4655 we scale the relative spectrum by F_A / F_R

- This is straightforward to implement in ISIS

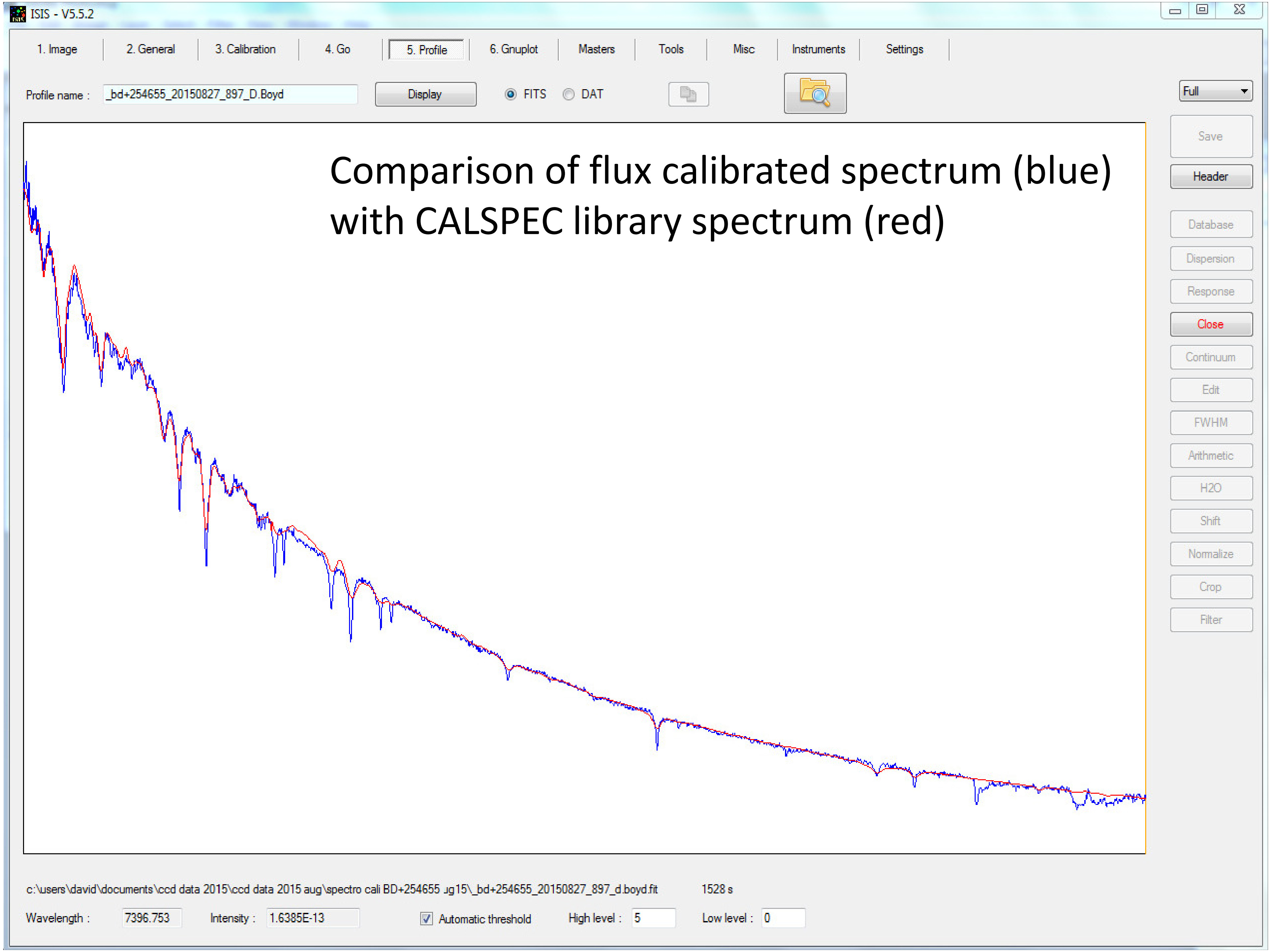


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name : _bd+254655_20150827_897_D.Boyd
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Compare
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Relative spectrum of BD+25 4655
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

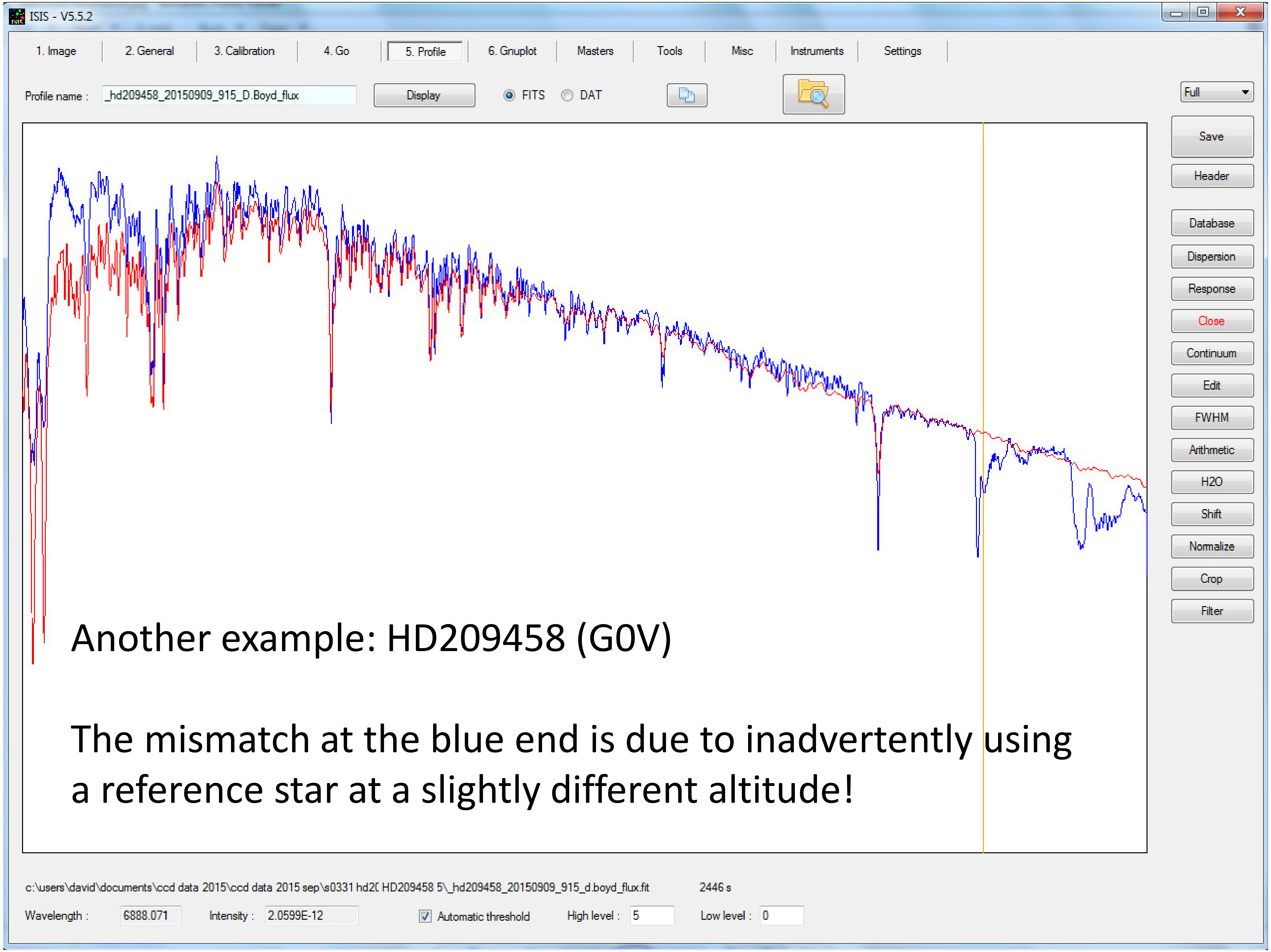

ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name : _bd+254655_20150827_897_D.Boyd
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Compare
Continuum
Edit
Close
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Relative flux transmitted by V filter
Line profile and continuum
FWHM : 3.799 A
FWHM : 220.921 km/s
Emission
Absorption
Position : 5155.9155 A
EW : 554.3121 A
Sum : 2279.6568
Sum : 2040.2929
Average : 0.7864
Median : 0.3534
Max : 2.5391
Min : 0.000E00
Deviation : 0.8938
SNR : 0.9
SNR (2) : 0.9
SNR (3) : 313.6
Close
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 : 4332.273
Intensity : 0.000000
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
Save
Header
Database
Dispersion
Response
Compare
Continuum
Edit
FWHM
Close
H2O
Shift
Normalize
Crop
Filter
Scale relative spectrum by F_A / F_R
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
F_A
Multiplied by a profile
Name : Astrodon V filter profile
Compute
Divide by a constant
Value : 2040.2929
Compute
F_R
Divide by a profile
Name : p_a1v
Compute
Power
Value : 1.0
Compute
Clip maximum value
Intensity : 1000.0
Compute
Normalize at maximal value
Compute
Close
Now absolute flux in erg/cm^2/sec/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
Save
Header
Database
Dispersion
Response
Close
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Comparison of flux calibrated spectrum (blue)
with CALSPEC library spectrum (red)
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 :
1.6385E-13
Automatic threshold
High level :
5
Low level :
0



Another example: HD209458 (G0V)

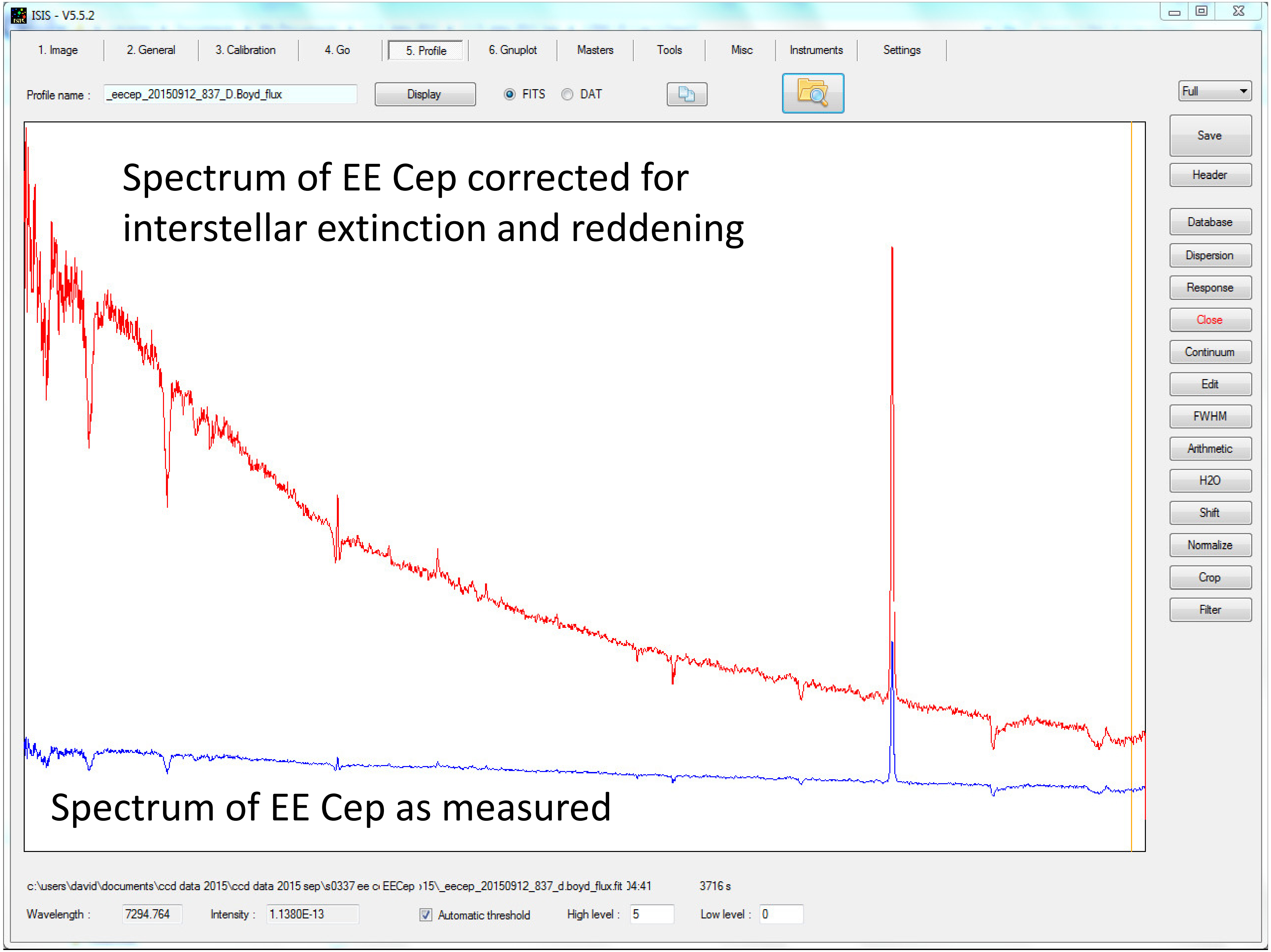
The mismatch at the blue end is due to inadvertently using a reference star at a slightly different altitude!

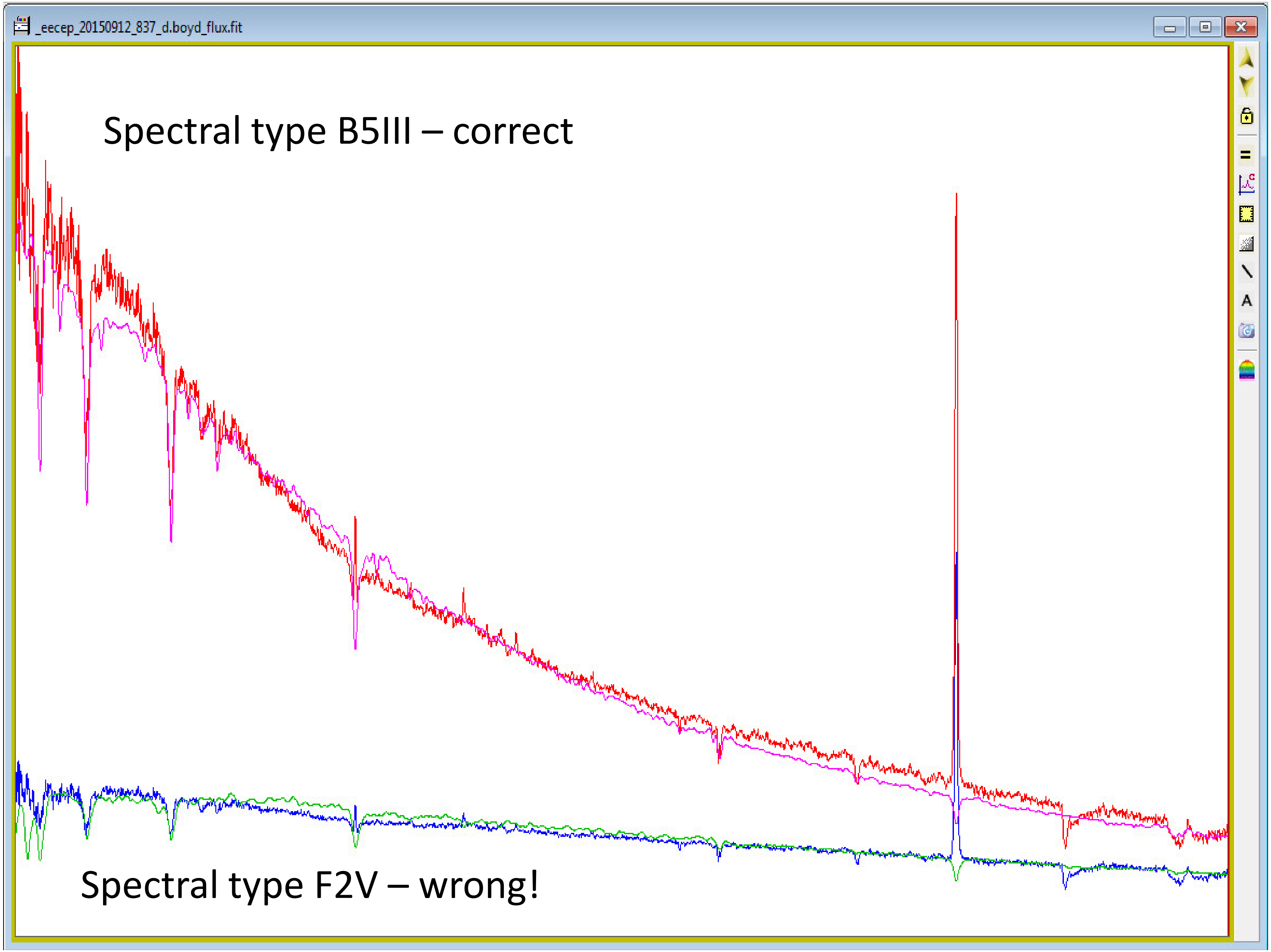
Correcting interstellar extinction and reddening – why do it?

If light from a star experiences a significant amount of both extinction and reddening due to the interstellar medium, this can change the spectral type we might infer from the spectrum

Only apply this correction if necessary for analysing the spectrum, in most cases it is not necessary

EE Cephei has a colour excess E(B-V) of 0.5


ISIS - V5.5.2
1. Image
2. General
3. Calibration
4. Go
5. Profile
6. Gnuplot
Masters
Tools
Misc
Instruments
Settings
Profile name : _eecep_20150912_837_D.Boyd_flux
Display
FITS
DAT
Full
Save
Header
Database
Dispersion
Response
Close
Continuum
Edit
FWHM
Arithmetic
H2O
Shift
Normalize
Crop
Filter
Spectrum of EE Cep corrected for interstellar extinction and reddening
Spectrum of EE Cep as measured
c:\users\david\documents\ccd data 2015\ccd data 2015 sep\s0337 ee c‹ EECep ›15_eecep_20150912_837_d.boyd_flux.fit)4:41
3716 s
Wavelength : 7294.764
Intensity : 1.1380E-13
Automatic threshold
High level : 5
Low level : 0


_eecep_20150912_837_d.boyd_flux.fit
Spectral type B5III – correct
Spectral type F2V – wrong!

Interstellar extinction and reddening – how to calculate it

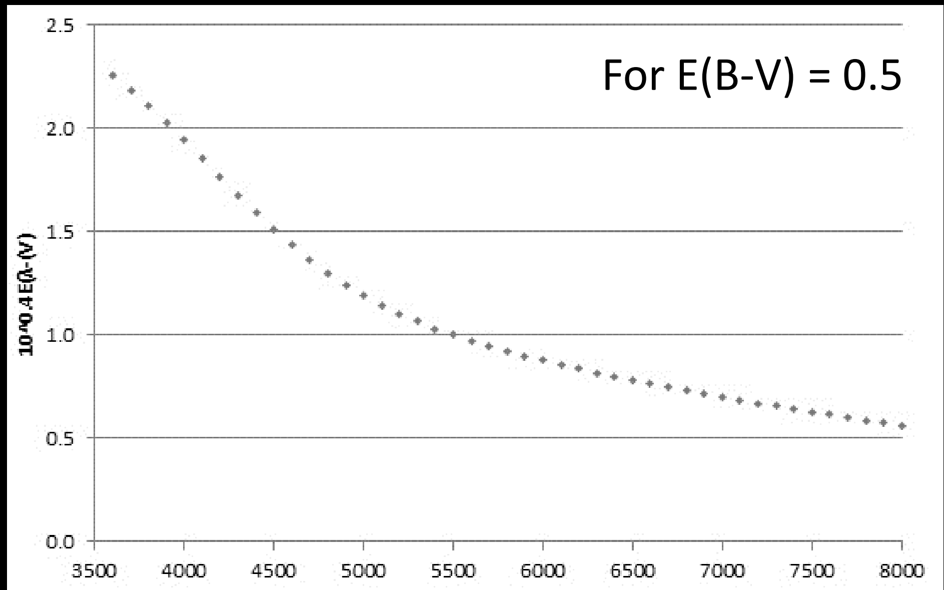
- E(B-V) is a measure of the colour excess of a star in magnitudes due to interstellar extinction
  – this can usually be found somewhere in the literature
- A(V) is the total extinction in magnitudes in the V band (5500Å)
- A(V) = R_V * E(B-V) where R_V is conventionally taken as 3.1 for the diffuse interstellar medium
- We can find values of the function A(λ)/A(V) in various references
- e.g. Cardelli et al. Astrophysical Journal, 345, 245 (1989)
- The generalised λ-V colour excess, E(λ-V) = A(λ)-A(V)
  (= 0 at 5500Å)

There are two corrections to be made

1. For extinction at 5500Å we scale the whole absolute flux spectrum by 10^[0.4*A(V)]

2. To correct for wavelength-dependent extinction or reddening we scale the spectrum by 10^[0.4*E(λ-V)]

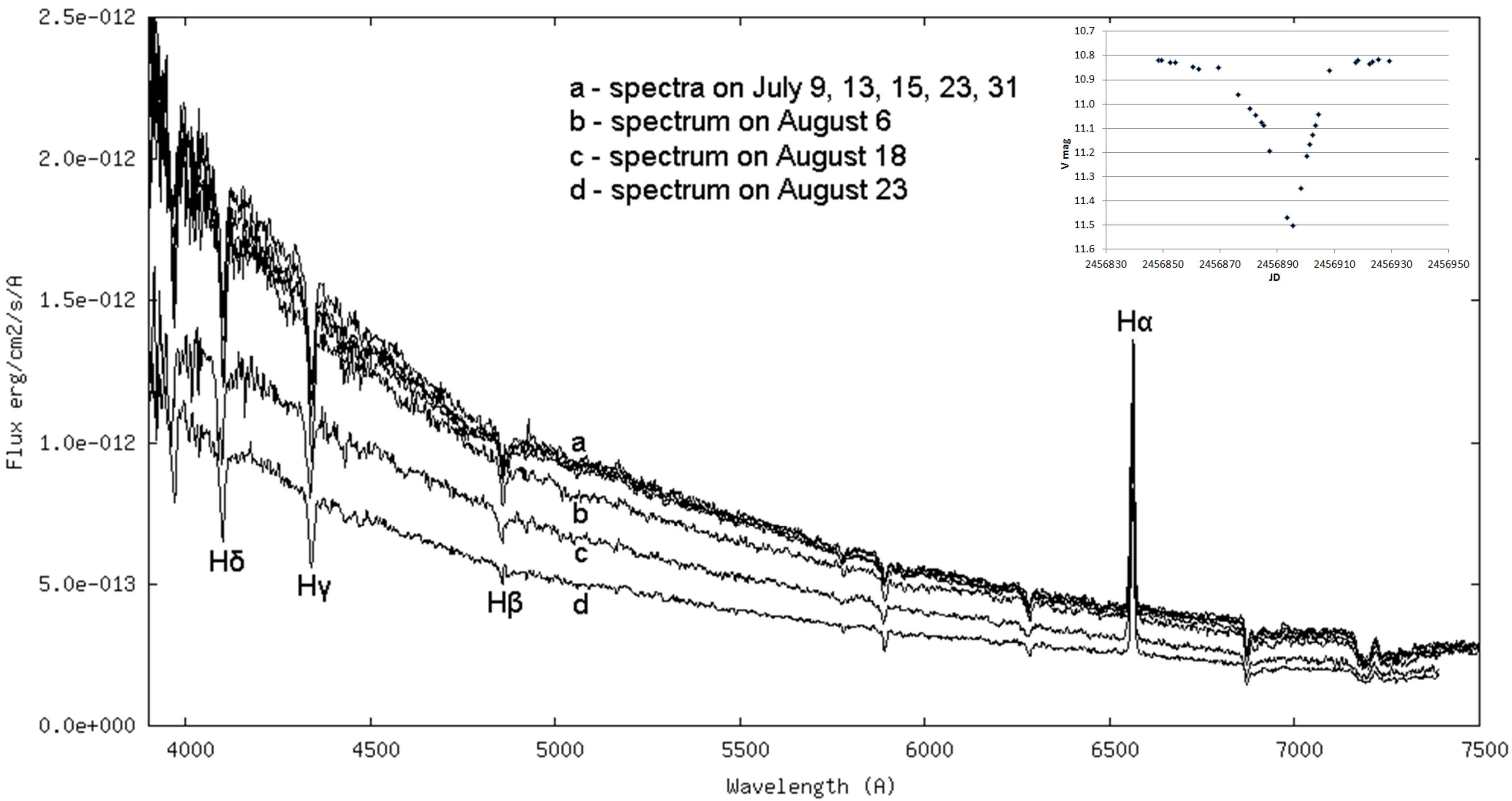
The latter can be calculated in a spreadsheet and exported as a scaling profile used to scale the absolute flux spectrum



Again these corrections are simple to apply in ISIS

Once a set of spectra have been corrected for flux and extinction they can be compared to reveal real physical changes in the source

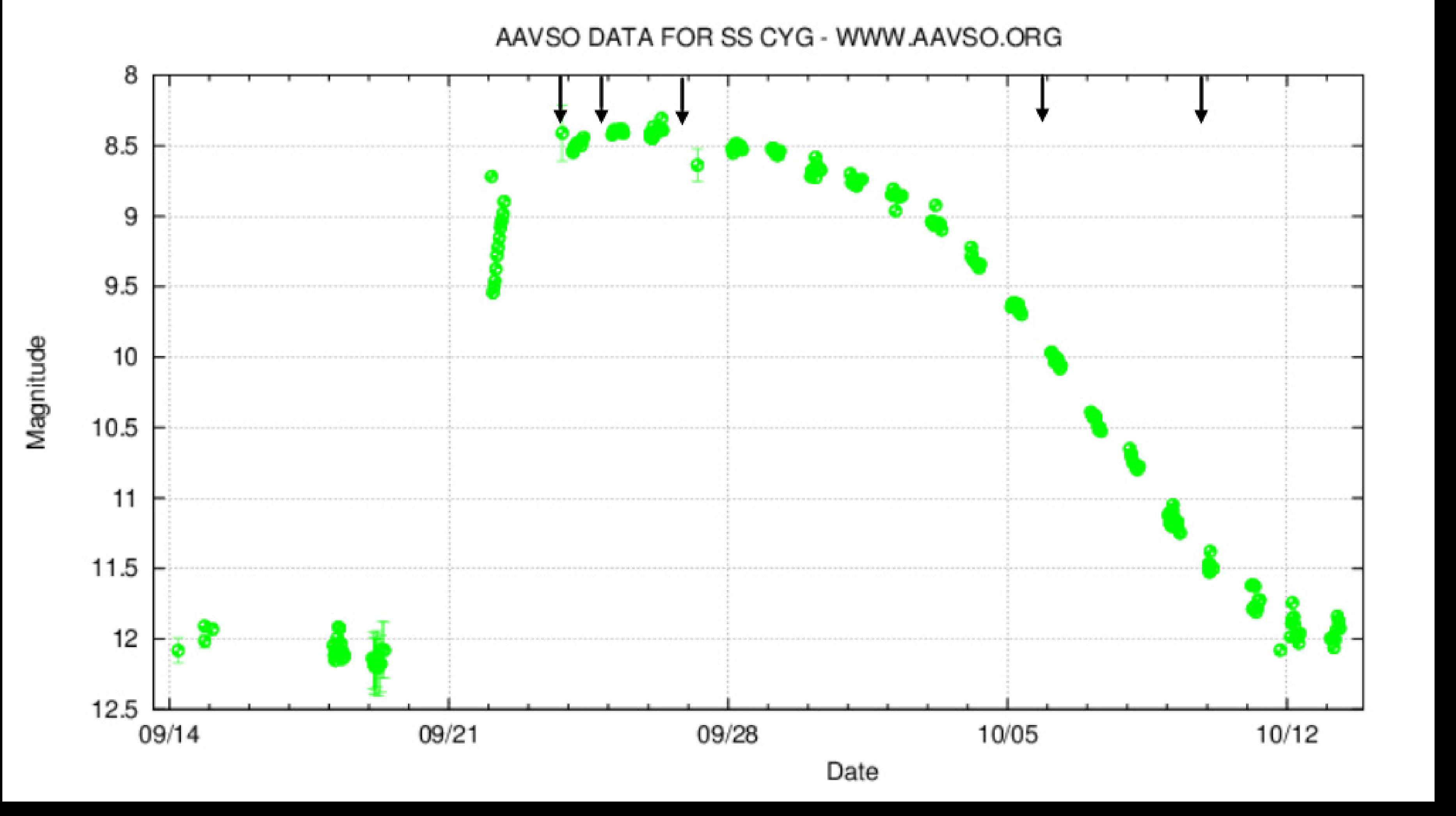
e.g. spectra of EE Cep during ingress to eclipse in 2014



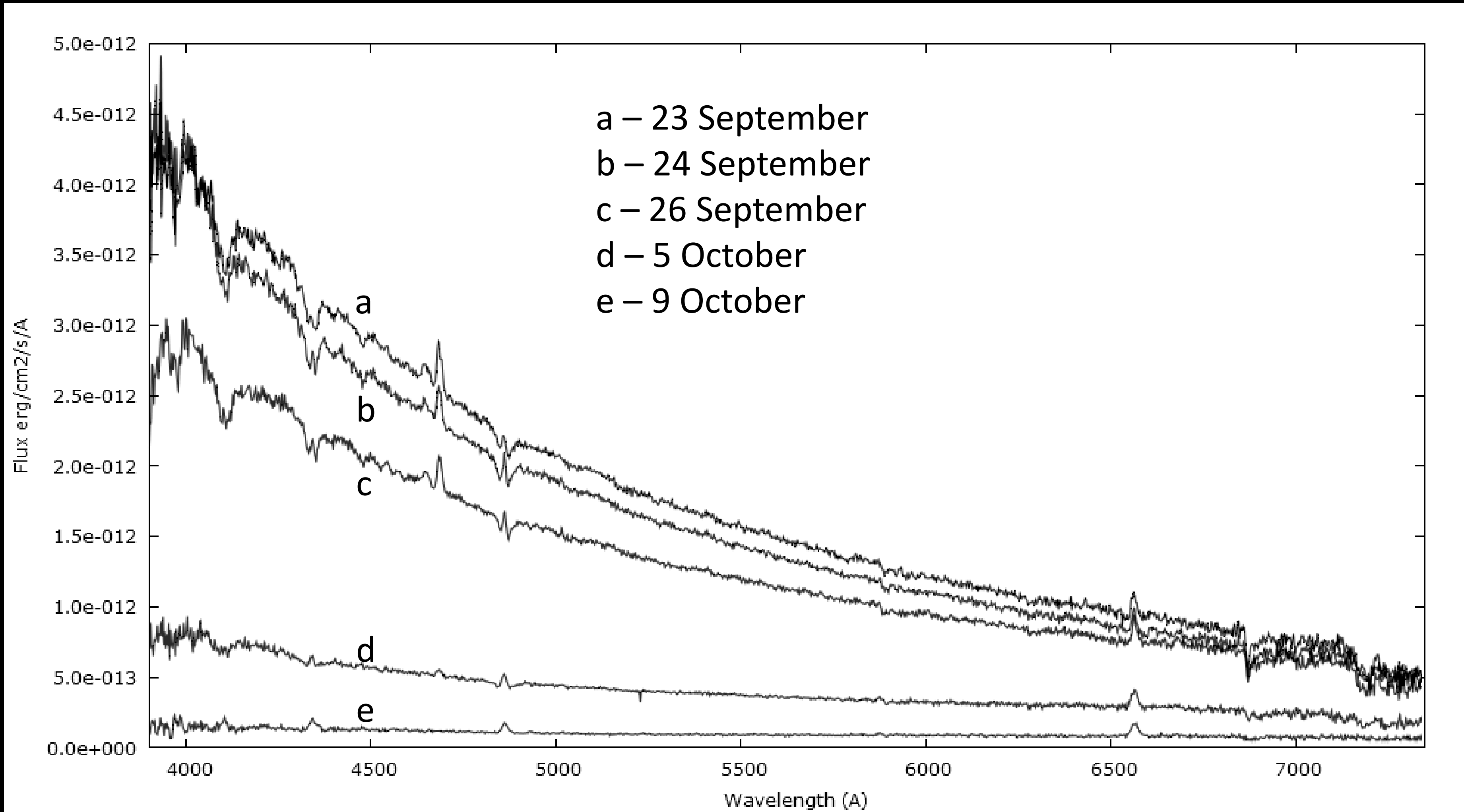
Some examples of observations with a LISA

SS Cygni

5 spectra were recorded during an outburst in Sep-Oct 2013 and flux calibrated using V magnitudes from the AAVSO database



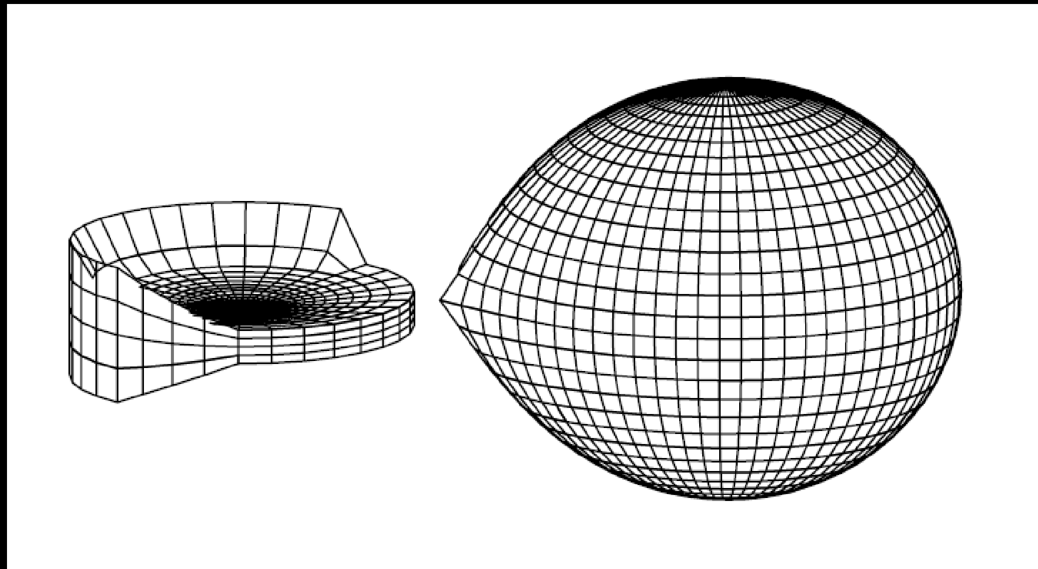
The reduction of 3 magnitudes in V over this period is equivalent to a 16x reduction in flux at 5500Å – which is exactly what we see



V Sagittae – a strange object!

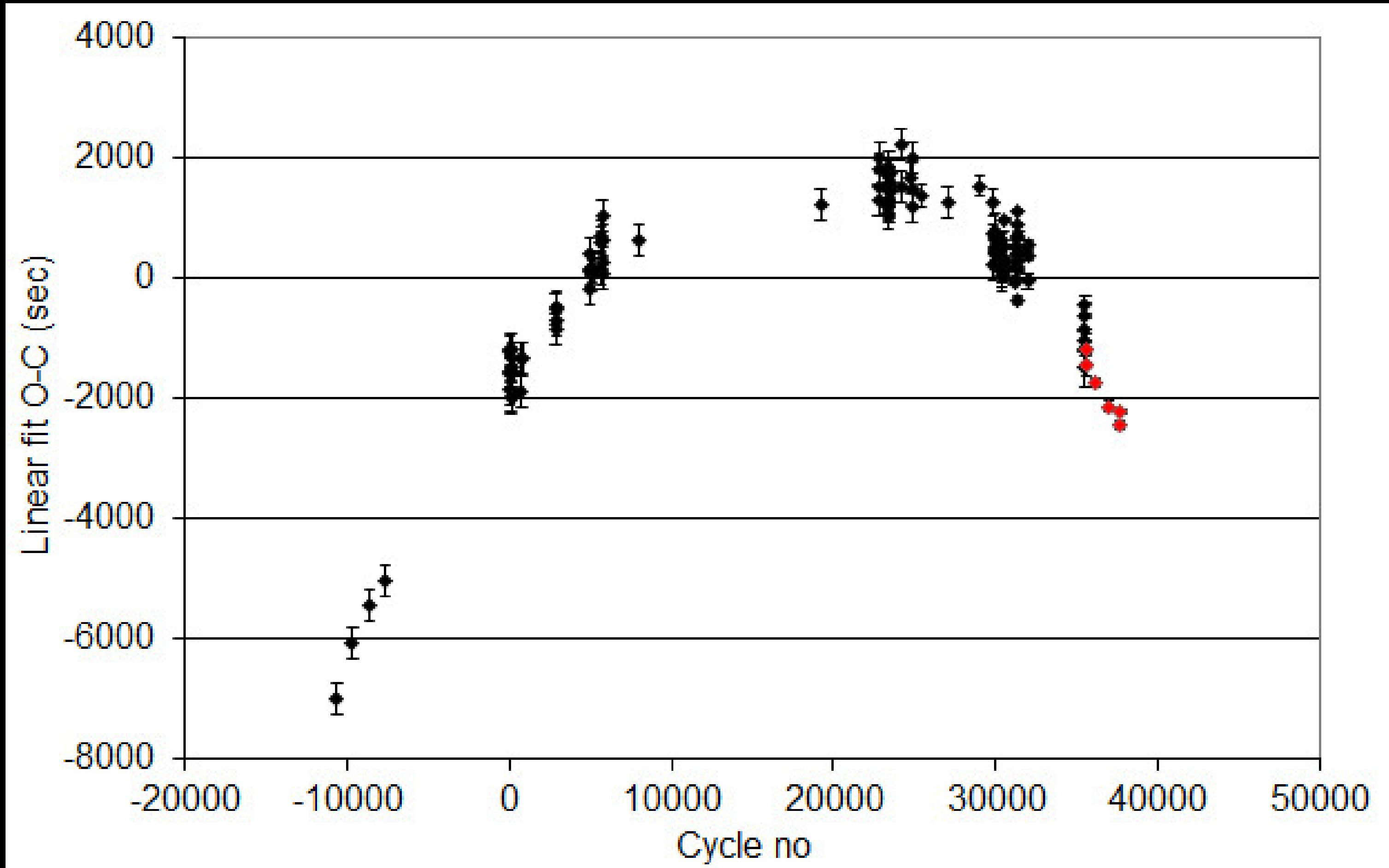
This is a peculiar eclipsing binary and supersoft X-ray source consisting of a WD, possibly surrounded by an accretion disc, which is accreting matter from a more massive secondary star and emitting a variable wind with both stars surrounded by a hot gaseous envelope

One possible model:



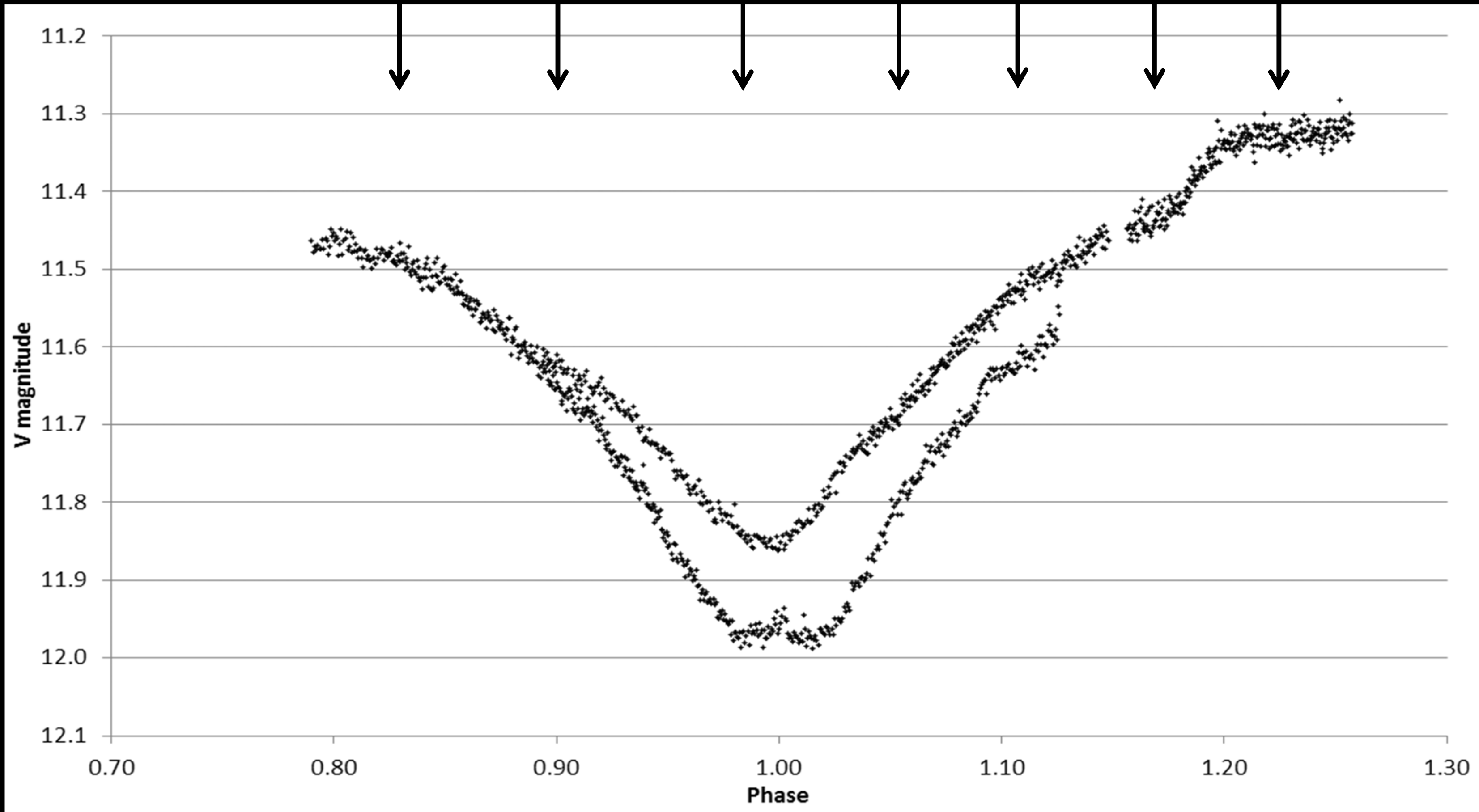
Hachisu & Kato, Astrophysical Journal, 598, 527, (2003)

Each published paper seems to propose a slightly different model!



Eclipse timing measurements over 70 years show that its 12.5 hour orbital period is steadily decreasing at the rate of $dP/dt = -5.24(5)*10^{-10}$ (0.017sec/yr)

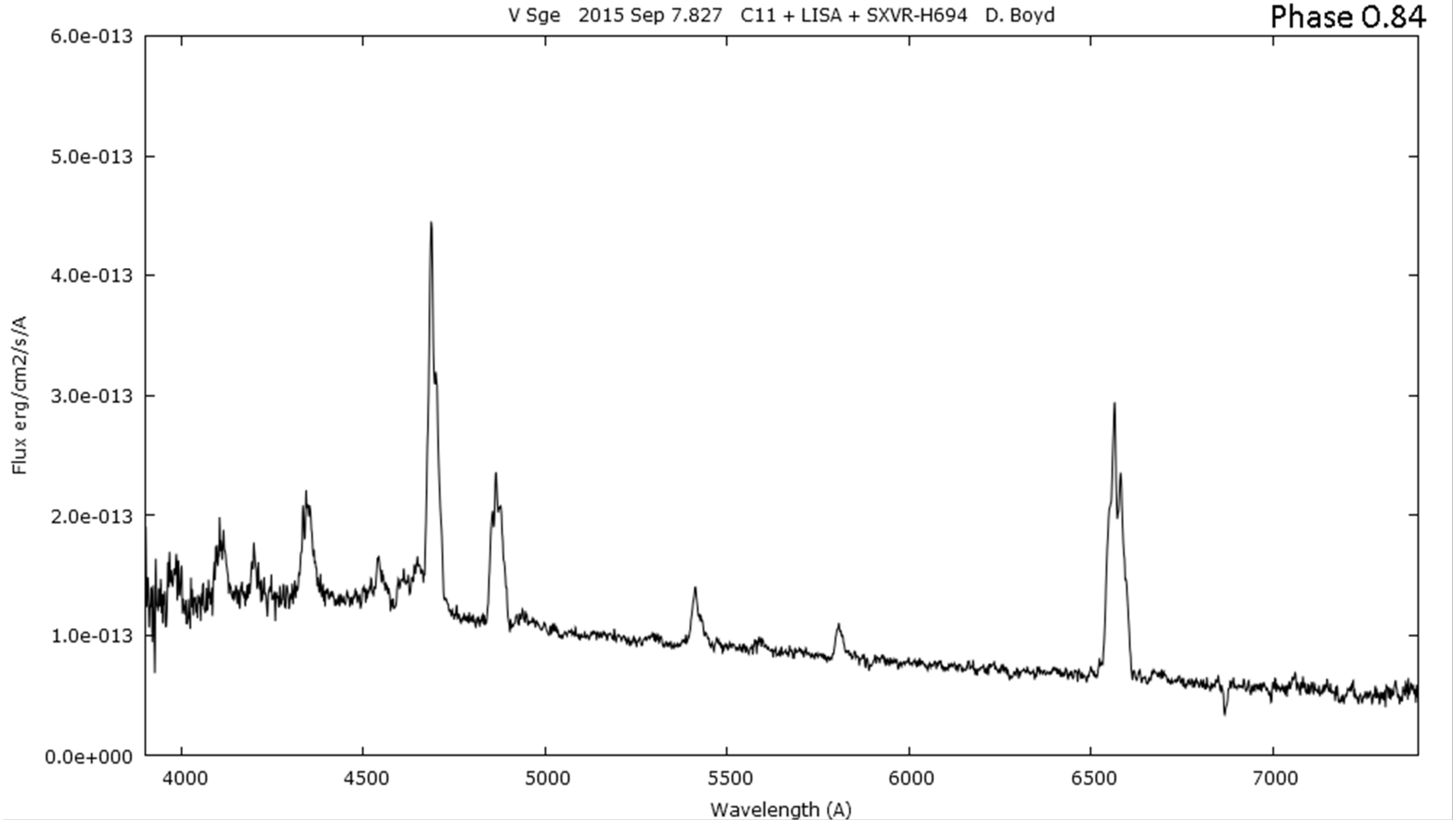
Primary eclipses on 6 & 7 Sept 2015 have quite different profiles



I recorded 7 spectra, flux-calibrated with concurrently measured mean V magnitudes during these two eclipses

This animation shows how the spectrum of V Sge changes through the eclipse

phase 1.00 = eclipse minimum



What we see:

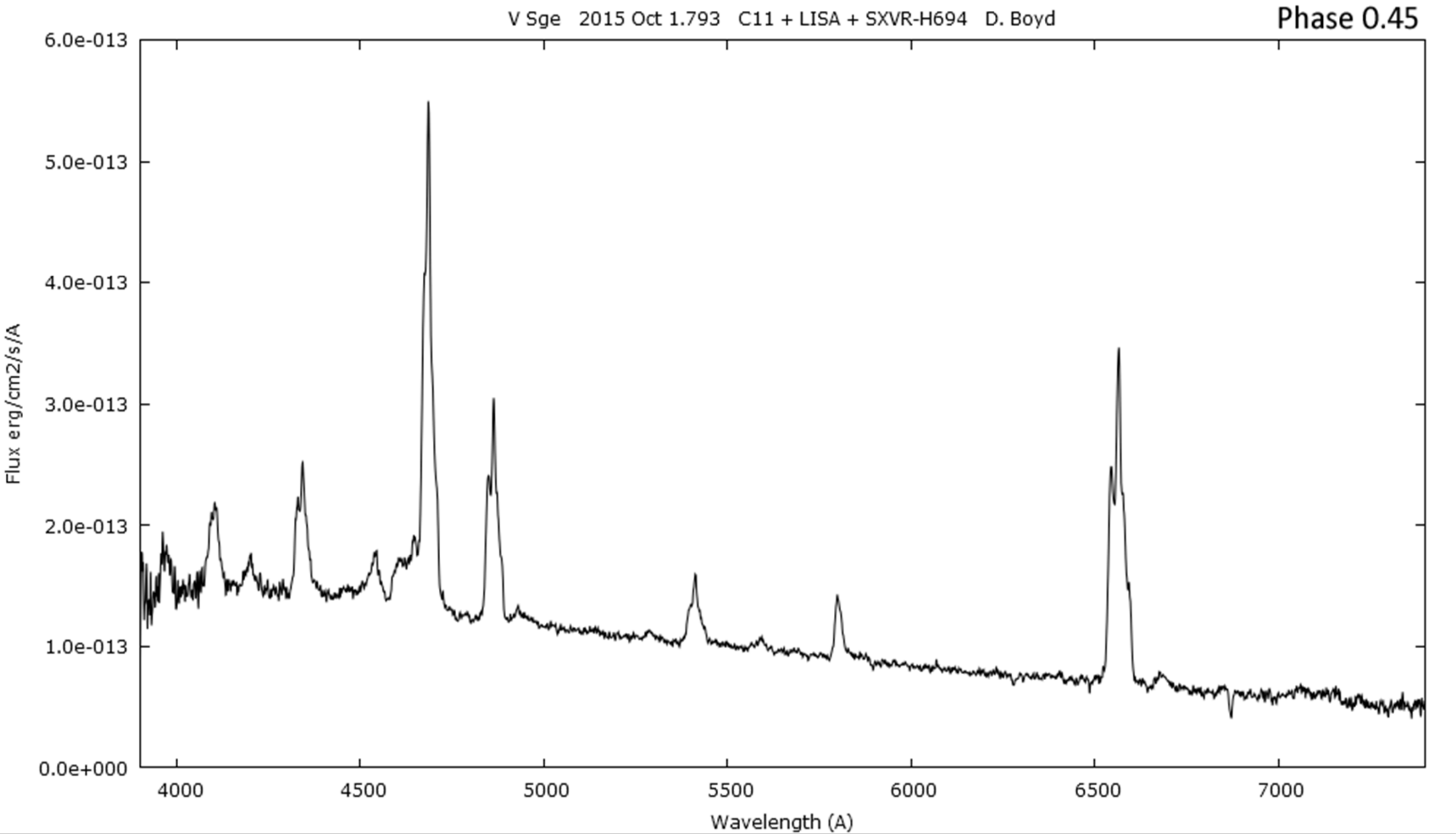
- Balmer and He II emission lines remain strong throughout the eclipse so can’t come from the WD which is being eclipsed
- Secondary peaks of these emission lines move from red-shifted to blue-shifted as the eclipse progresses with a relative velocity of ±780km/s

Similar secondary peaks were reported in Williams et al., MNRAS, 219, 809 (1986)

Most models seem to agree that:

- the uneclipsed Balmer and He II emission lines arise within the gaseous envelope around both stars
- the source of the red- and blue-shifted components is not understood but could be material in orbit around the WD

And just to make it more interesting – in the shallow secondary eclipse the side peaks move from blue to red!



Measuring radial velocity with a LISA

I wanted to answer 3 questions :

a) Is it possible?

b) How well can it be done?

c) Can it produce useful results?

Initial impression is that it is going to be difficult

Measuring lines in the calibration lamp spectrum at 6000Å gives FWHM ~2.7 pixels at 1.8 Å/pixel = ~5Å

So spectral resolution R is ~1200

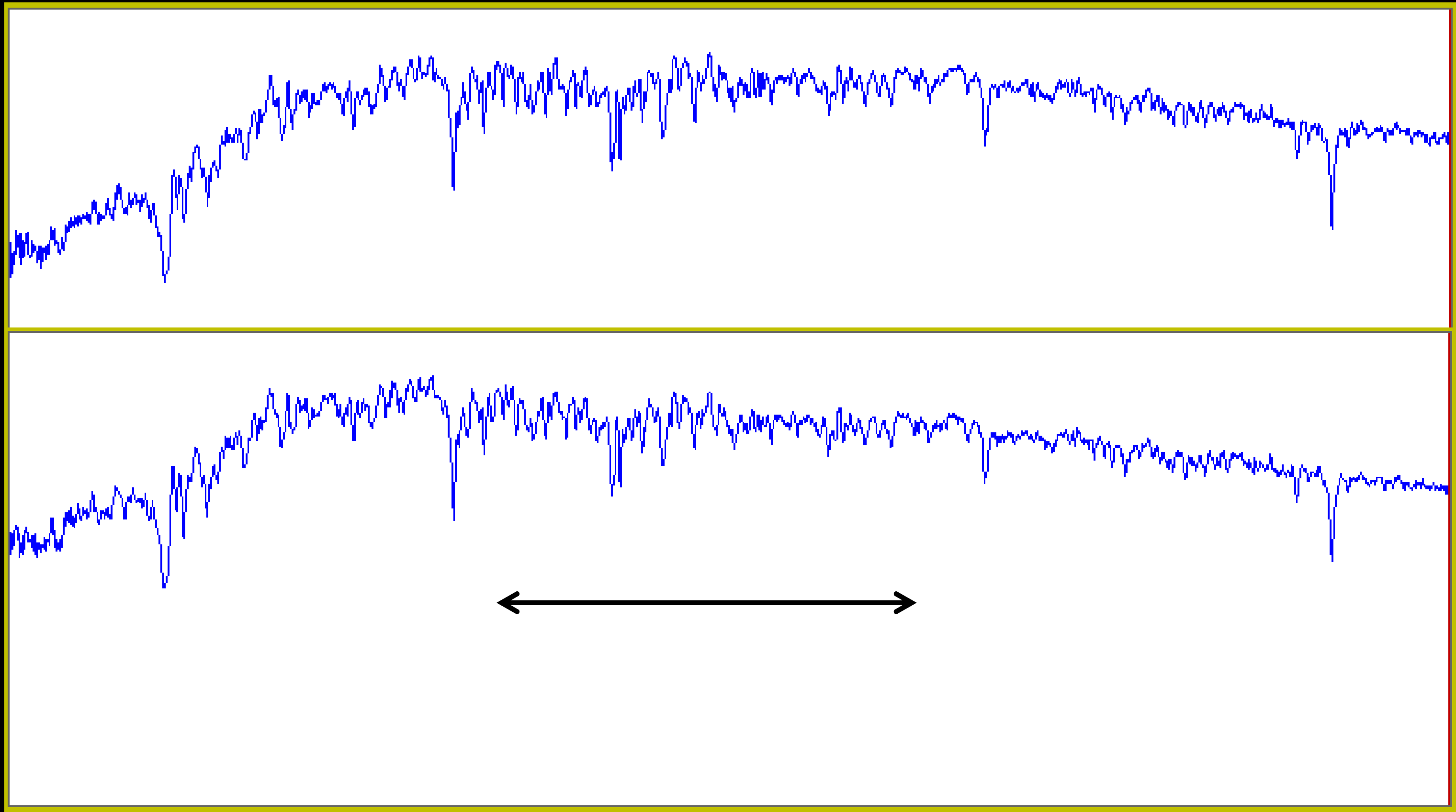
Taken as a RV resolution, this is equivalent to ~250 km/s

However, calibration using 16 lines in the Ar/Ne lamp gives

rms = 0.1 to 0.2Å

This indicates that a correlated analysis could do a lot better

ISIS includes a function for cross-correlating two spectra

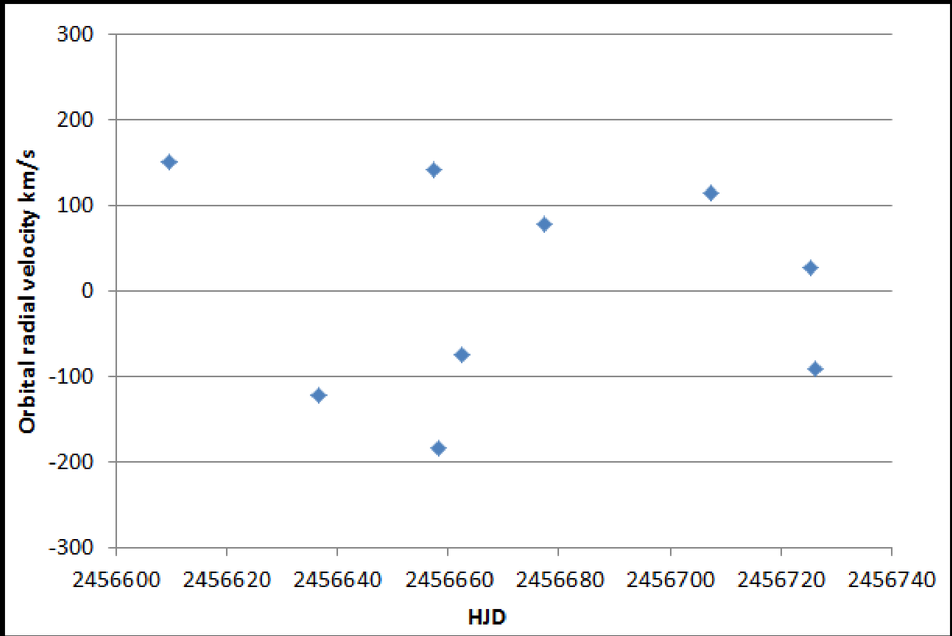


After applying heliocentric corrections, the relative wavelength shift between the two spectra gives their relative radial velocity

$$d\lambda/\lambda = v/c$$

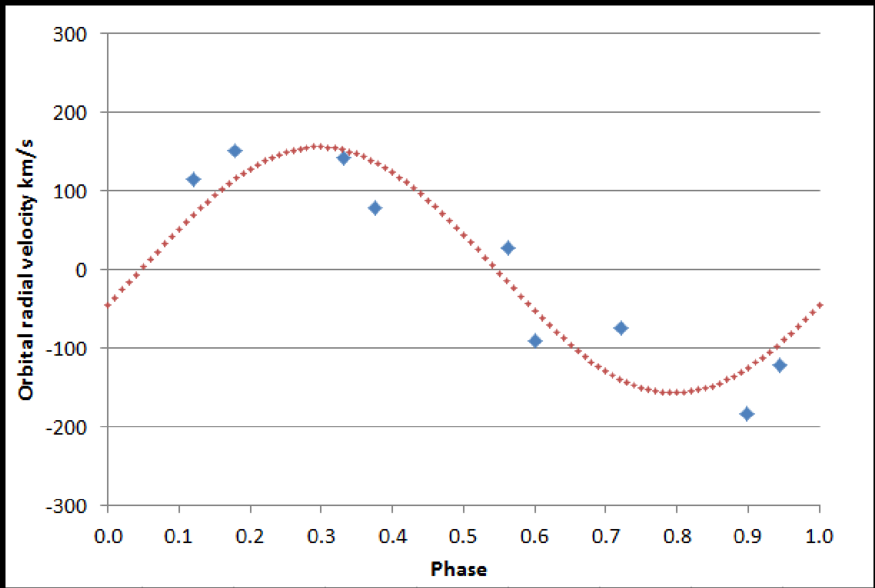
Boris Gaensicke (Warwick Univ) suggested I try to measure the RV of a post common envelope binary (pre-CV) V471 Tau

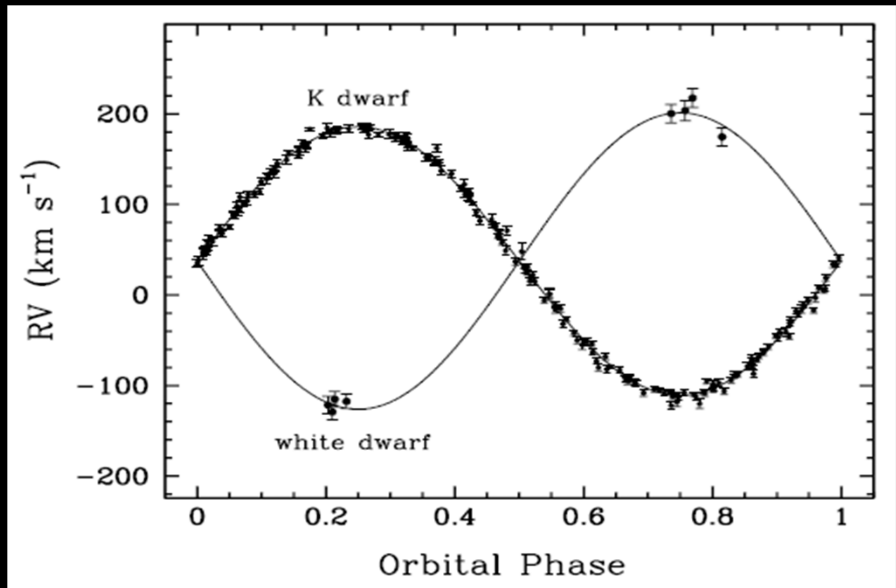
This contains a cool K2V main sequence star and a hot WD with Porb ~0.5 d and RV amplitude of ±160 km/s



Spectra were taken on 9 nights and RVs calculated relative to the first night using the cross-correlation function in ISIS

Phased on the published orbital period of 0.521183d these measurements compare quite well to published RV curves





The rms scatter relative to the sine curve is ~45 km/s

This looked hopeful, measuring RVs was indeed possible

– but how well could it be done?

Experience showed that several factors are important if more precise results are to be obtained:

a) Temperature of the LISA must have stabilised before starting

b) LISA must be carefully focused at the operating temperature

c) Calibration lamp spectra must be taken frequently

d) Star spectrum should have many lines - eg spectral type F or G

e) Spectrum should be cropped to remove main telluric features

Next step was to test the procedure using a known binary star

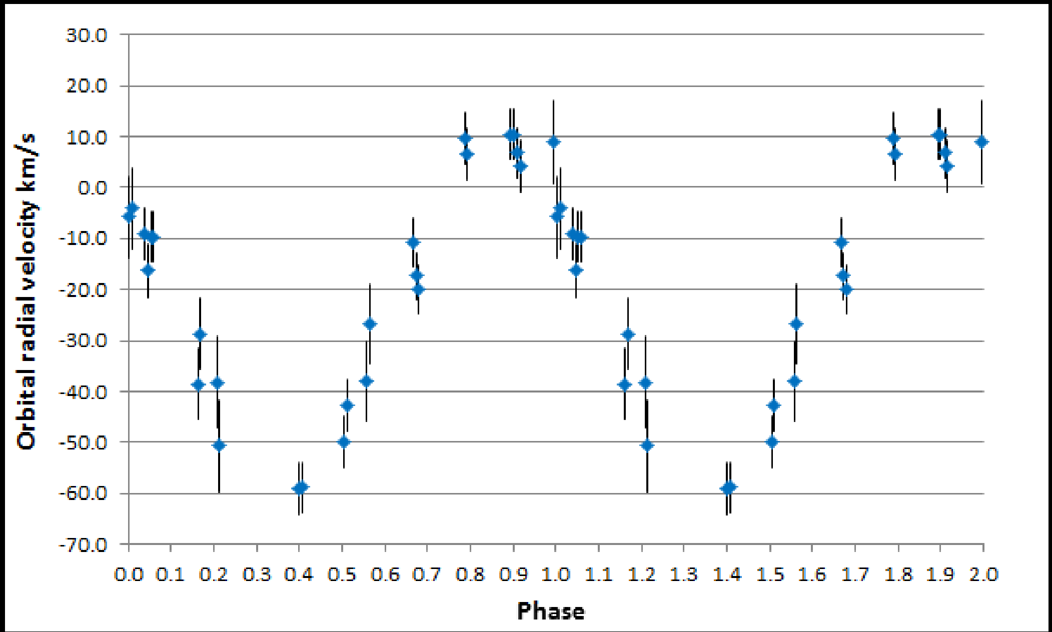
HD116514 is a 9.3 mag single lined spectroscopic binary with period 5.939 days, K1 = ±37.82 km/s and spectral type G5V

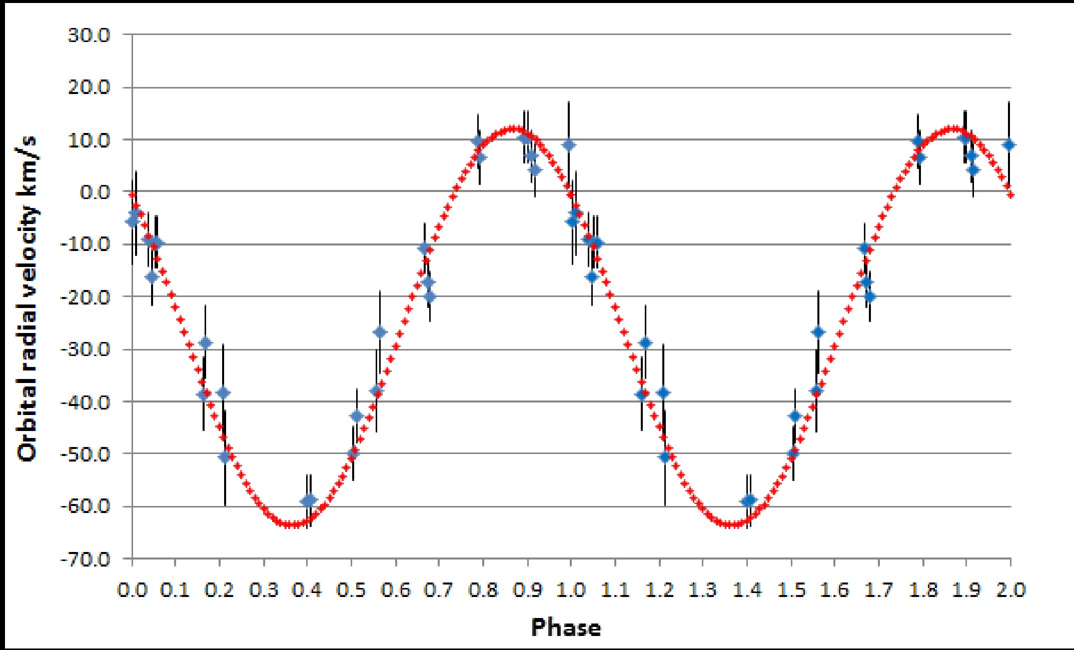
A reference spectrum was taken on the first night (average of 3)

26 spectra were taken on 12 nights and RVs calculated relative to the reference spectrum using CCF in ISIS

RV data phased on Porb = 5.939 days

Each error bar is std dev of 2 or 3 RV measurements made on the same night





Plot of the RV data with the actual RV variation (e = 0)

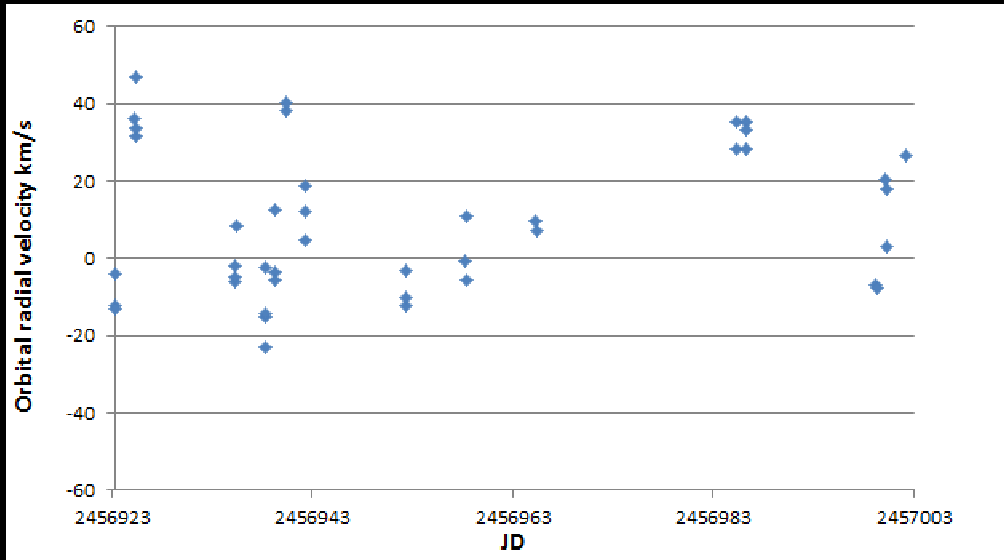
rms scatter about the real RV curve is <u>5.2 km/s</u>

Zero point of the RV variation is arbitrary as it was not measured relative to an RV standard star

So now we know how well it can be done – how can we use it?

Boris Gaensicke suggested I look at a mag 10.8 star, spectral type G whose spectrum showed a UV excess – could this be evidence of a white dwarf companion?

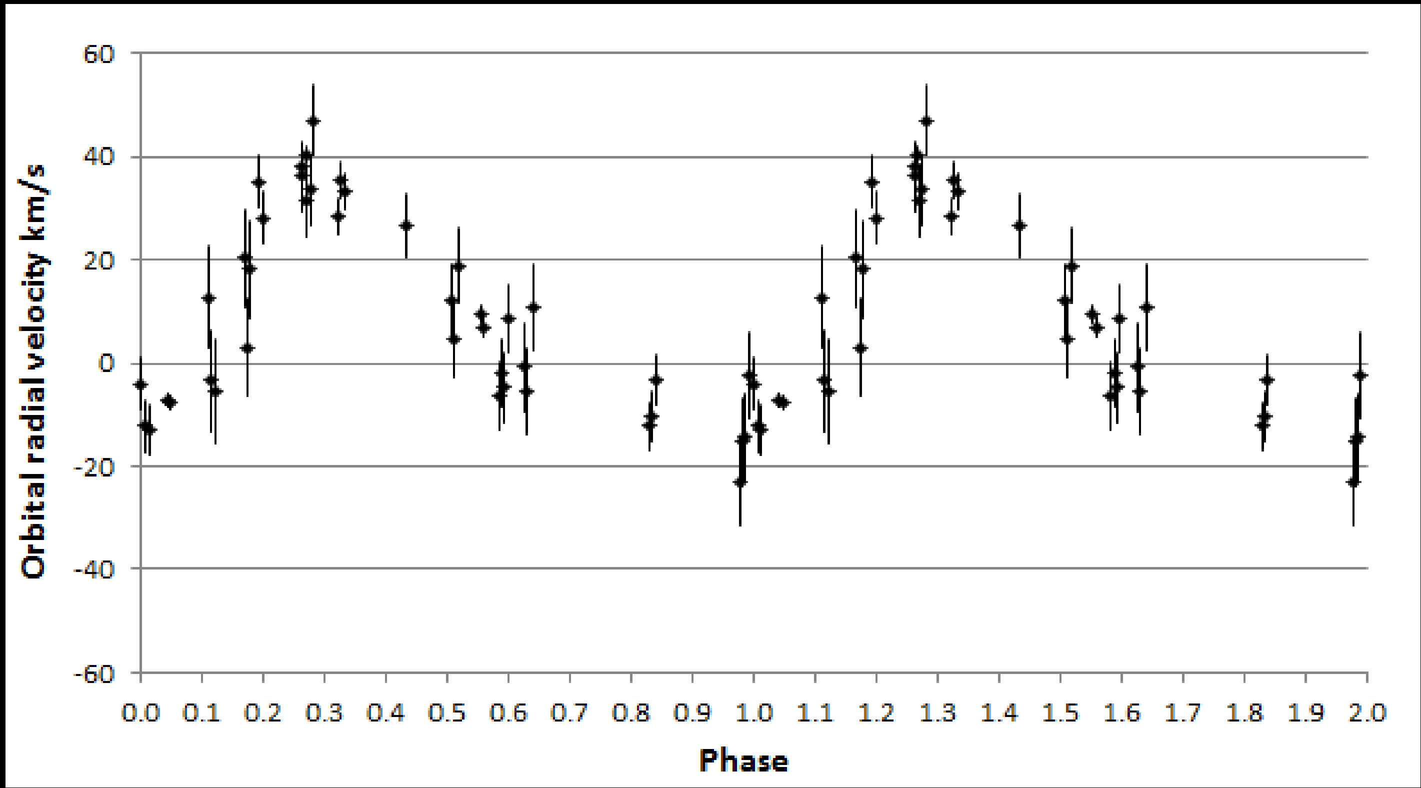
42 spectra taken on 15 nights



Mean intra-night std dev was 5.7 km/s

Period analysis revealed a periodic signal at 7.563 days

RV plot phased on this period showed this object is probably an eccentric post common envelope binary – a new discovery!



So measuring RVs carefully with the LISA can produce useful results!

I hope this gives you an idea of the scientific potential of an instrument like the LISA spectrograph

Thank you for listening