Workshop on Observational Techniques

Basic introduction: spectrographs

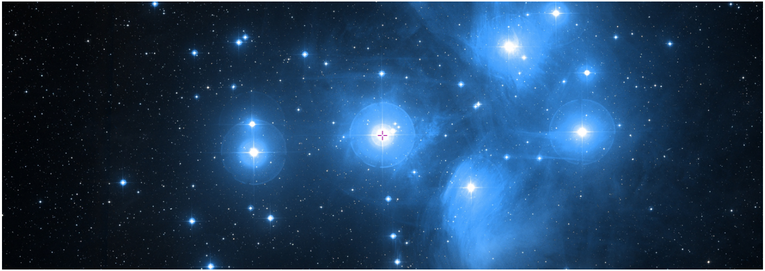
Matti Dorsch[1]

[1]University of Potsdam

21. August 2023

at Ondřejov observatory

What do we want to achieve?



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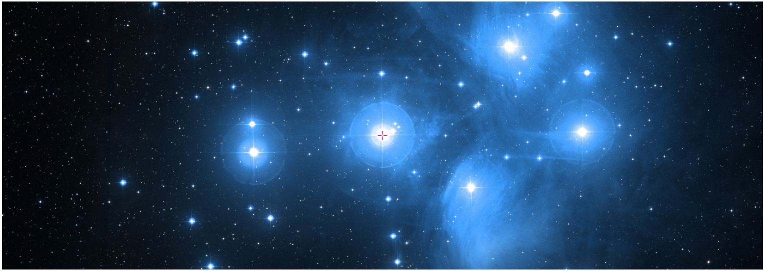

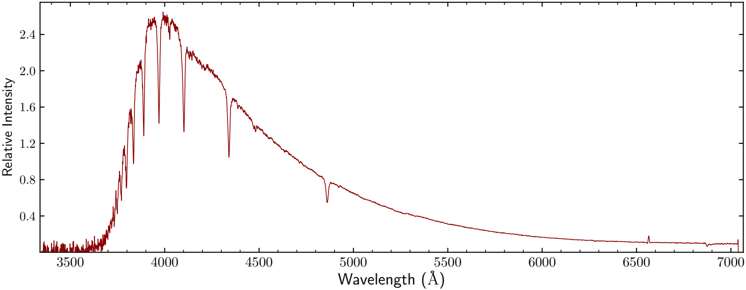

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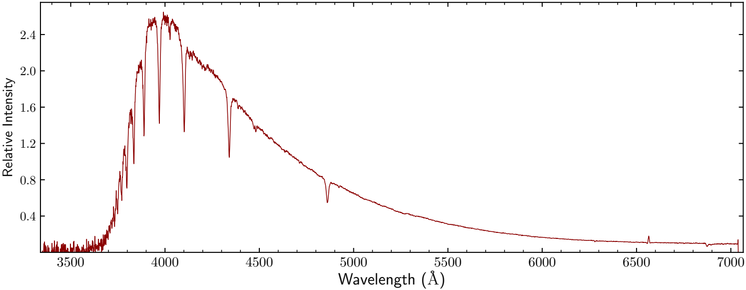


Compromise between

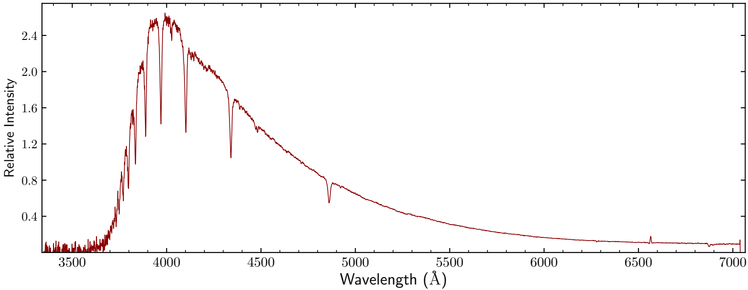
Large wavelength range

High efficiency

High spectral resolving power $R = \lambda / \Delta\lambda$

Accurate wavelength calibration

What do we want to achieve?



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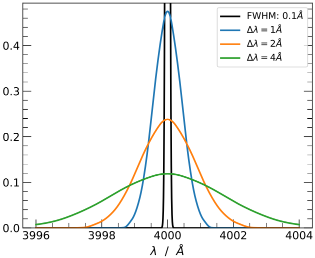


First-order spectroscopy

Long slit spectrograph

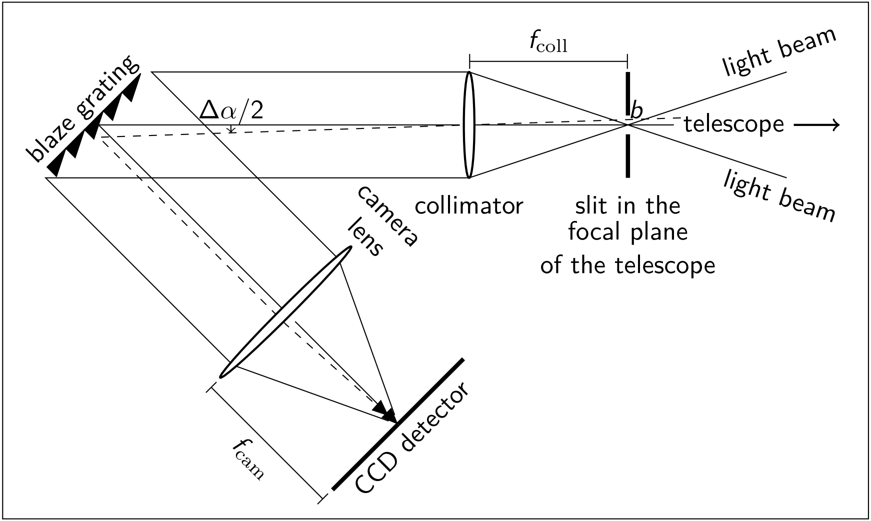
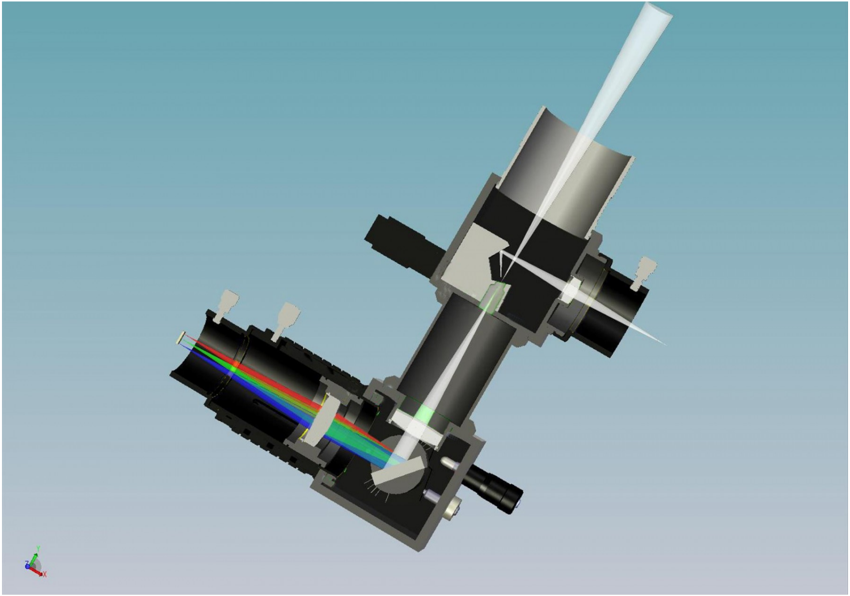


Figure: Schematic beam path in a long slit spectrograph.

A simple spectrograph



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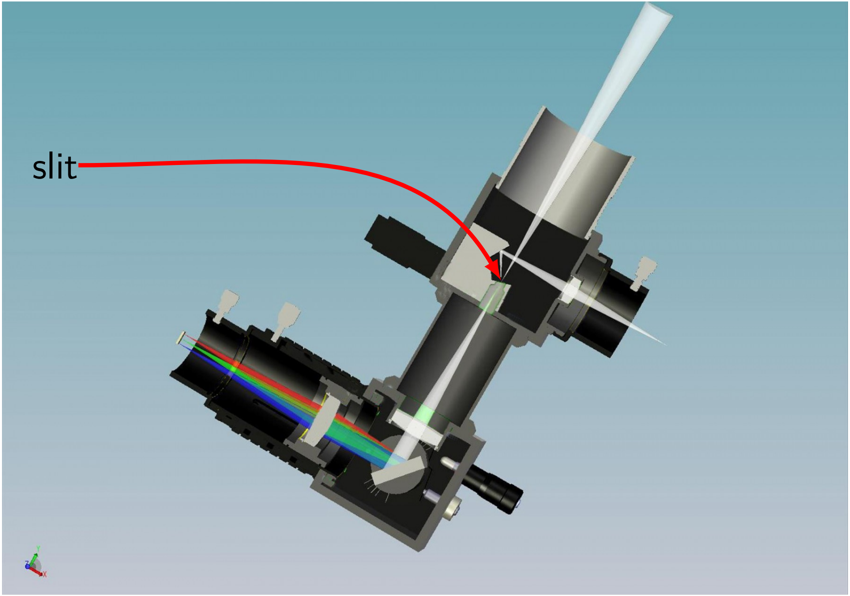

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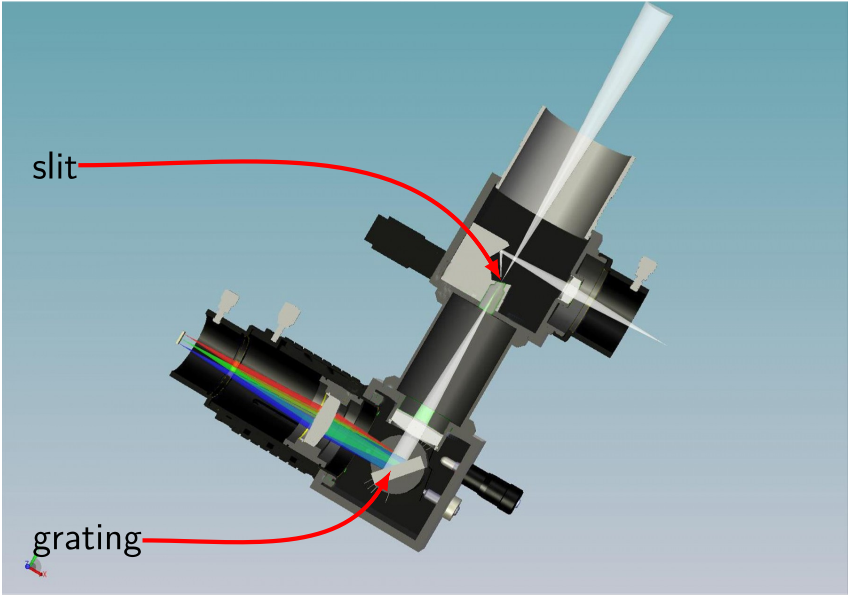

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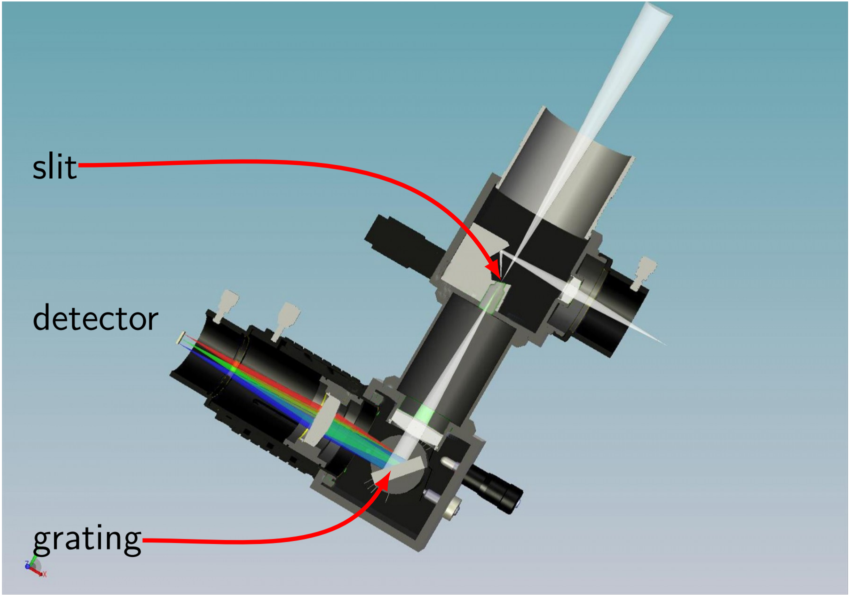


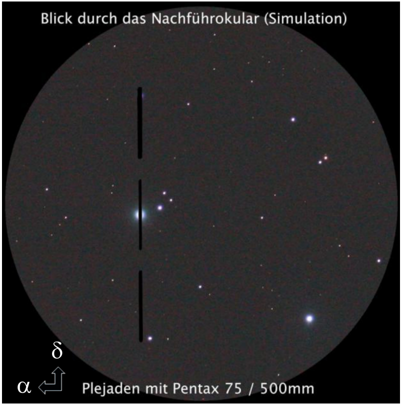
slit

detector

grating

Slits

Why do we need a slit?

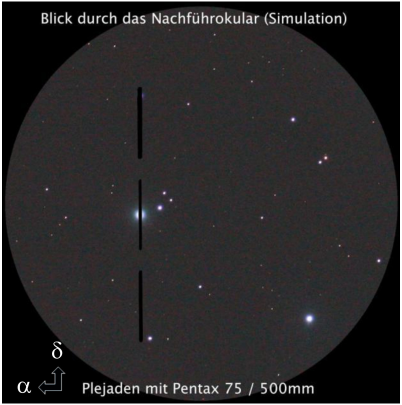


Which slit width do we choose?

Slits

Why do we need a slit?

- take spectrum of *one* object



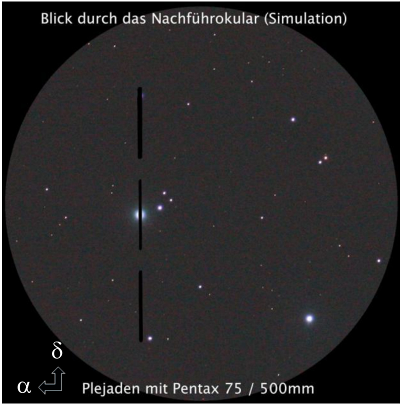
Which slit width do we choose?

Slits

Why do we need a slit?

- take spectrum of *one* object
- slit width $>$ PSF:
  seeing-limited resolution
- slit width $<$ PSF:
  slit-limited resolution
  (also extended objects)
- Typically: 10 to 1000 $\mu\mathrm{m}$

Which slit width do we choose?



Slits - light loss

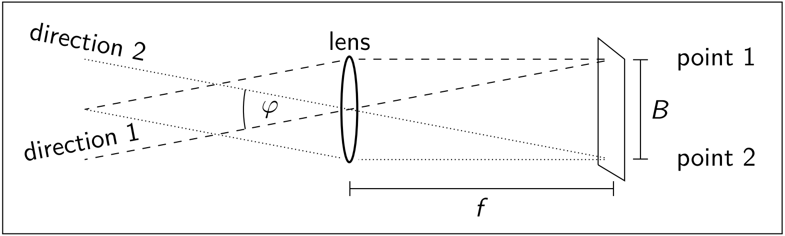


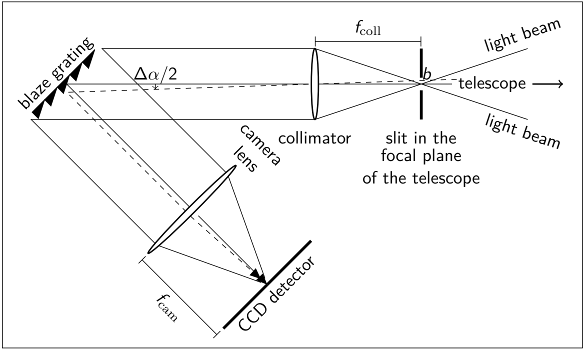
Figure: Image scale for a lens with focal length f and infinite object distance.

$$\frac{\varphi}{2} \approx \tan\frac{\varphi}{2} = \frac{B}{2f} \qquad \rightarrow \qquad B = f \cdot \varphi$$

$$\left.\begin{array}{l}\text{Typical seeing} \rightarrow \varphi \approx 2.5'' \\ f_{\mathrm{Perek}} = 63.5\,\mathrm{m}\end{array}\right\} \text{Projected size on slit } B \approx 770\,\mu\mathrm{m}$$

Slits - resolution

The slit used for OES is $b = 600\,\mu\mathrm{m} < 770\,\mu\mathrm{m}$! Why?



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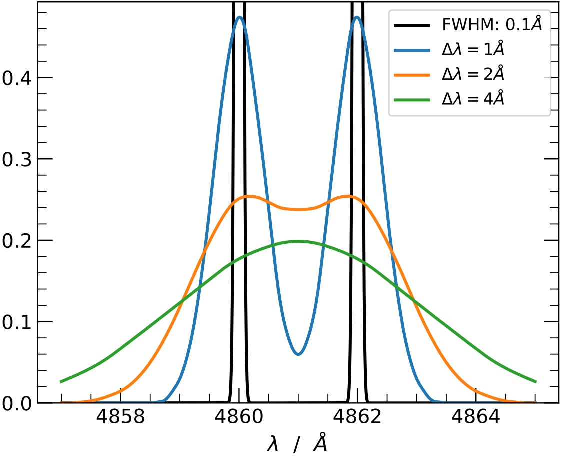

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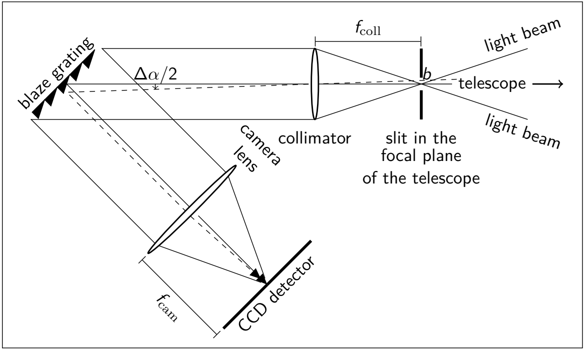

Figure: Schematic beam path in a long slit spectrograph.

Reminder: $\Delta\alpha \overset{\mathrm{b \ll f_{coll}}}{=} \frac{b}{f_\text{coll}}$, $n\lambda \overset{\text{interference}}{=} d \cdot (\sin\alpha + \sin\beta)$

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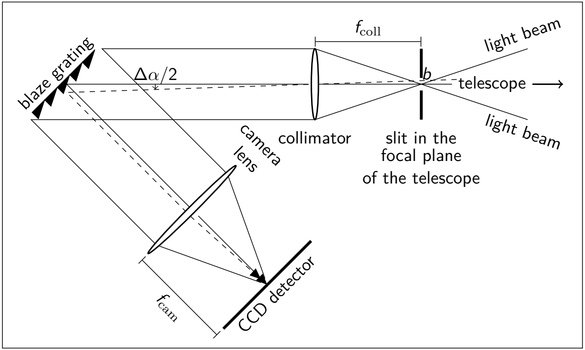


Figure: Schematic beam path in a long slit spectrograph.

Reminder: $\Delta\alpha \overset{\mathrm{b \ll f_{coll}}}{=} \frac{b}{f_{\mathrm{coll}}} \rightarrow \Delta\lambda \overset{lin.}{\approx} \frac{\partial\lambda}{\partial\alpha}\Delta\alpha = \frac{d}{n}\cos\alpha\Delta\alpha \overset{\mathrm{n=1}}{=} \mathrm{const.}$

Slits - resolution

The slit used for OES is $b = 600\,\mu\mathrm{m} < 770\,\mu\mathrm{m}$! Why?

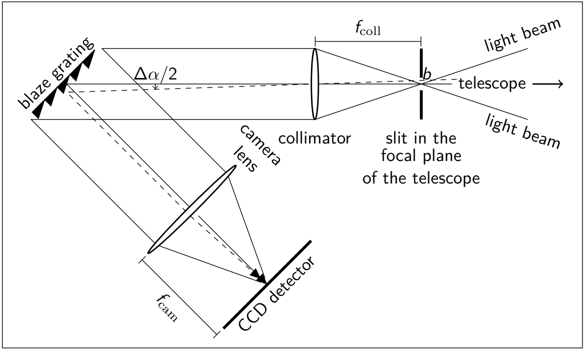
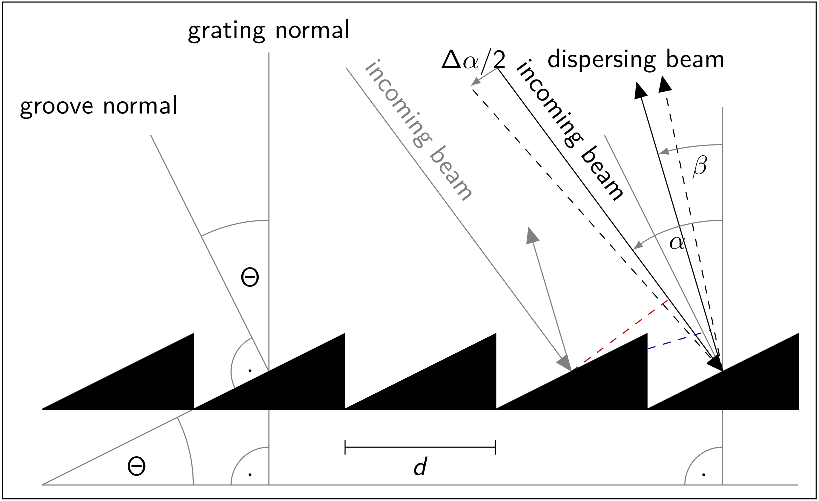


Figure: Schematic beam path in a long slit spectrograph.

Reminder: $\Delta\alpha \overset{\mathrm{b} \ll \mathrm{f_{coll}}}{=} \frac{b}{f_{\mathrm{coll}}} \to R_{\mathrm{slit}} = \frac{\lambda}{\Delta\lambda_{\mathrm{slit}}} = \frac{n f_{\mathrm{coll}}}{d\, b \cos\alpha}\lambda$

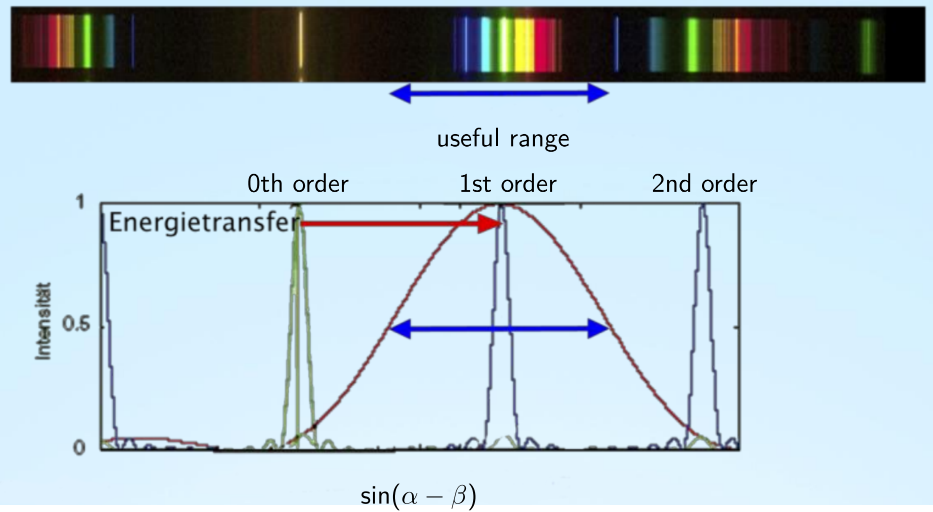
Blaze grating - interference condition



$\boxed{n\lambda \overset{\text{interference}}{=} \Delta s = d \cdot (\sin\alpha + \sin\beta)}$, order $n \in \mathbb{N}$; $\alpha + \beta \overset{\text{class.}}{=} 2\Theta_B$

Δs: path difference between each groove

Blaze grating - diffraction orders



$$n\lambda_n^0 = d \cdot (\sin\alpha + \sin(2\Theta_B - \alpha)),\ \lambda_n^0 = \text{blaze wavelength (max. intensity)}$$

Blaze grating - blaze function

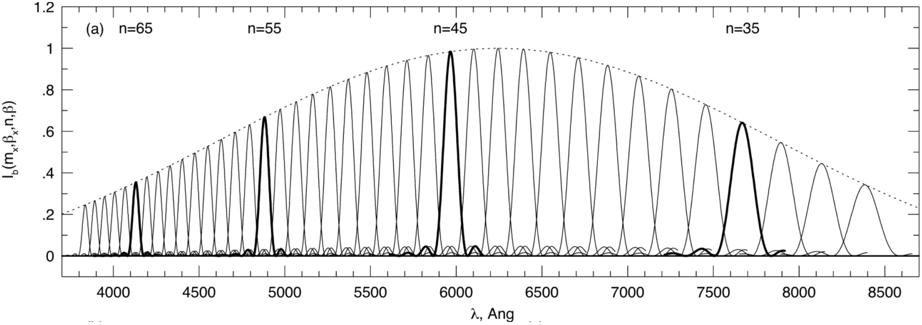
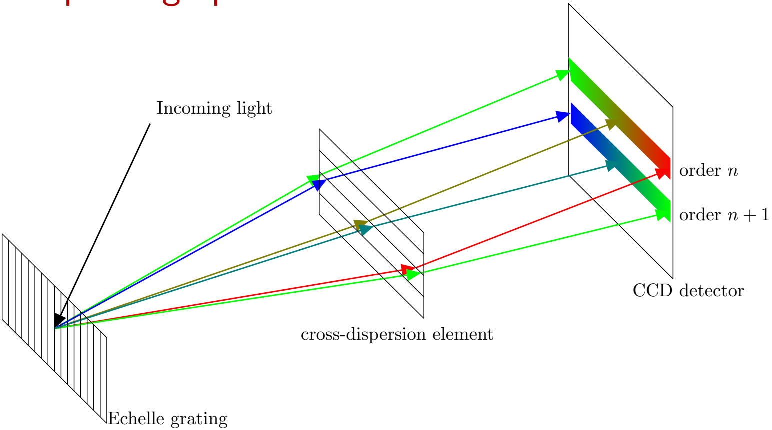


Figure: Dispersion and Blaze function $(\sin(x)/x)^2$ for a cross-dispersed échelle spectrograph.

Échelle spectrograph



- separate overlapping orders by cross-dispersion element
- optimized for high incidence angles and high orders: $\Theta_B = 69^\circ$ for OES

$$R_{\text{Échelle}} \approx \frac{f_{\text{coll}}}{b\cos\alpha}[\sin\alpha + \sin(2\Theta_B - \alpha)] \approx \text{constant} \approx 50000$$

Blaze grating - efficiency

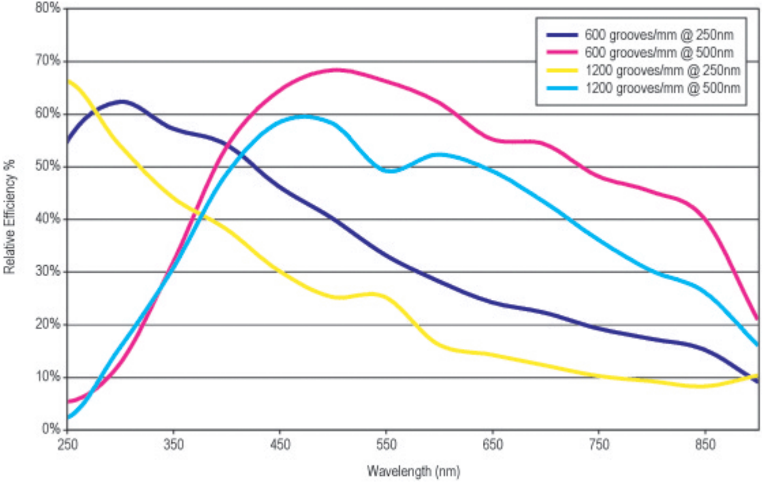


Figure: Typical efficiency curves for blazed holographic gratings (edmundoptics).

CCD detector - efficiency

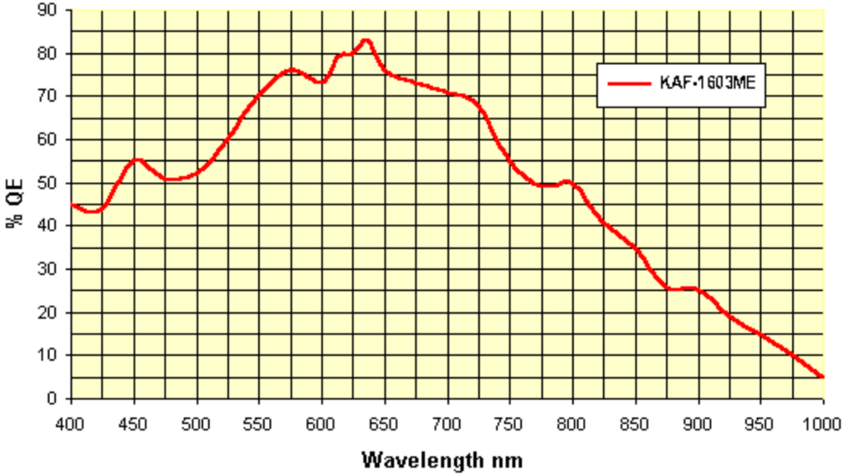


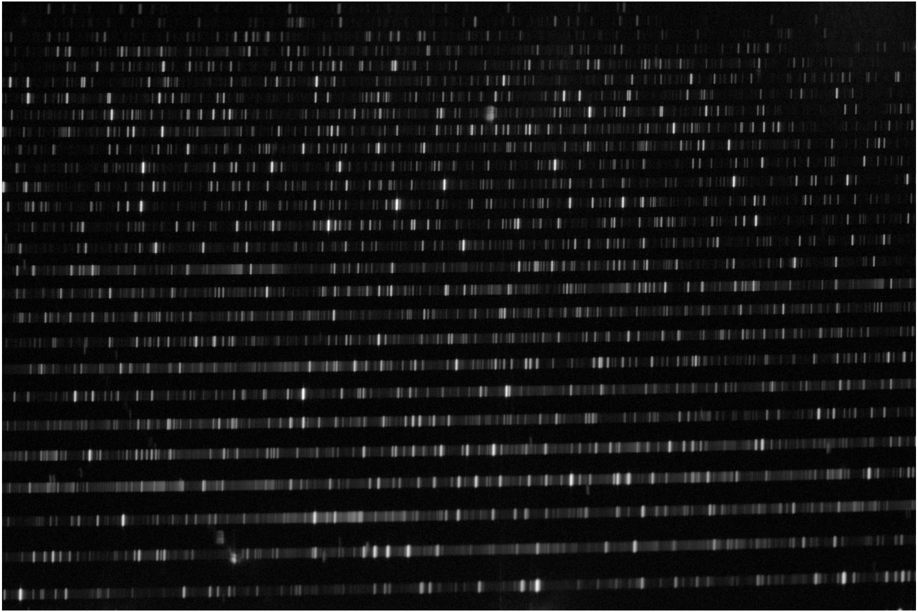
Figure: Quantum efficiency = % incident photons detected (SBIG ST-8XME).

Observation

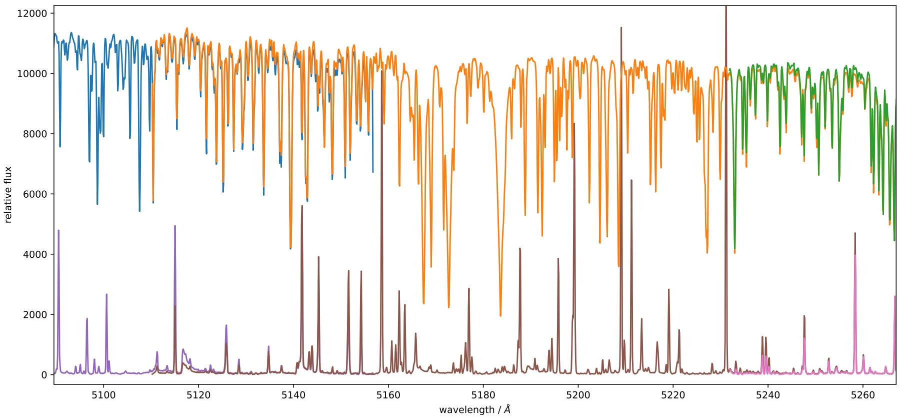
Raw images

Raw images

Raw images



Raw images


12000
10000
8000
6000
4000
2000
0
relative flux
5100
5120
5140
5160
5180
5200
5220
5240
5260
wavelength / Å

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame

For each of these:

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame
- *Flat-field* frame

For each of these:

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame
- *Flat-field* frame
- *Calibration (arc)* frame

For each of these:

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame
- *Flat-field* frame
- *Calibration (arc)* frame

For each of these:

- *Bias* frame:
  - used to remove the CDD *readout signals*, including constant offset
  - taken with shortest exposure time and closed shutter
  - included in dark frame, required if $t_{\mathrm{exp,dark}} \neq t_{\mathrm{exp,science}}$

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame
- *Flat-field* frame
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For each of these:

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  - used to remove the CDD *readout signals*, including constant offset
  - taken with shortest exposure time and closed shutter
  - included in dark frame, required if $t_{\mathrm{exp,dark}} \neq t_{\mathrm{exp,science}}$
- *Dark* frame:
  - thermal excitation of electrons in the CCD leads to a constant background noise
  - also: hot/cold pixels/columns
  - taken with the same exposure time and temperature as science frame
  - has to be subtracted from science frame

Reduction steps

Bias frame

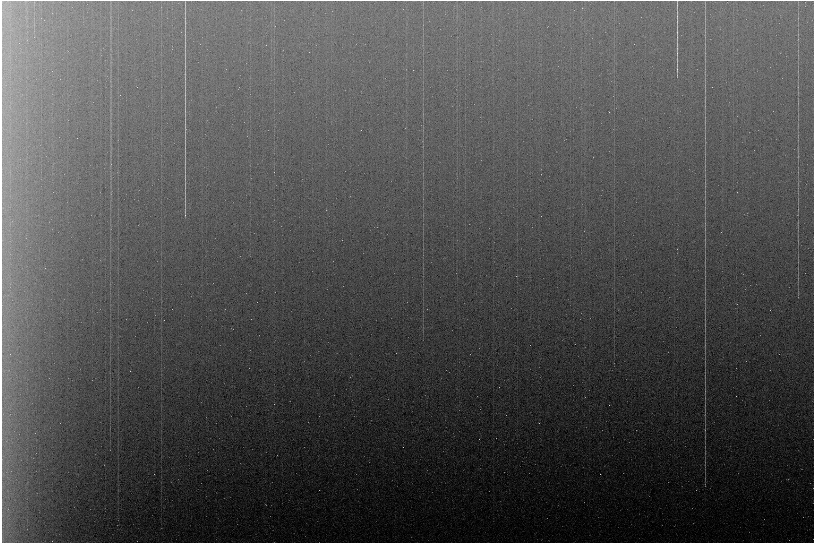


Figure: Median of 10 bias frames (closed shutter, shortest t_{exp}, log scale).

Bias frame

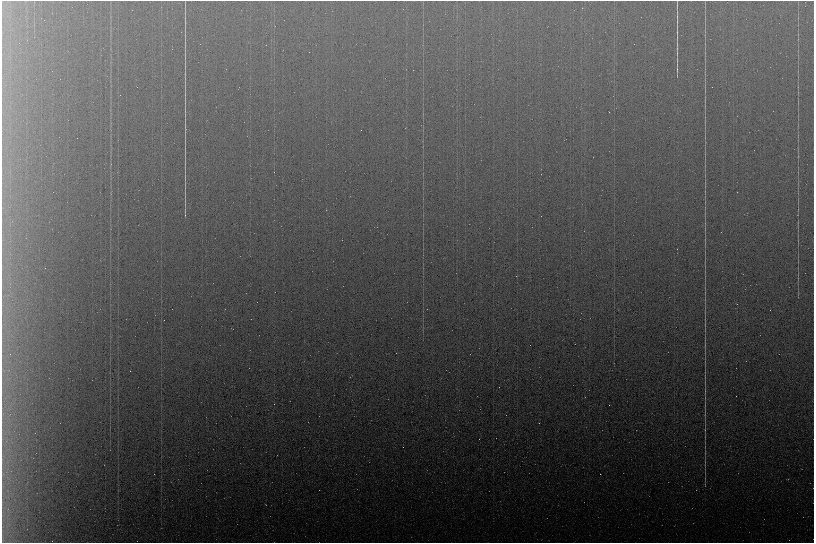


Figure: Median of 10 bias frames (closed shutter, shortest t_{exp}, log scale).

Dark frame / Cosmics

Figure: Dark frame detail, 3600s exposure (log scale).

Dark frame / Cosmics

Figure: Dark frame detail: median of five 3600s exposures (log scale).

Average frames

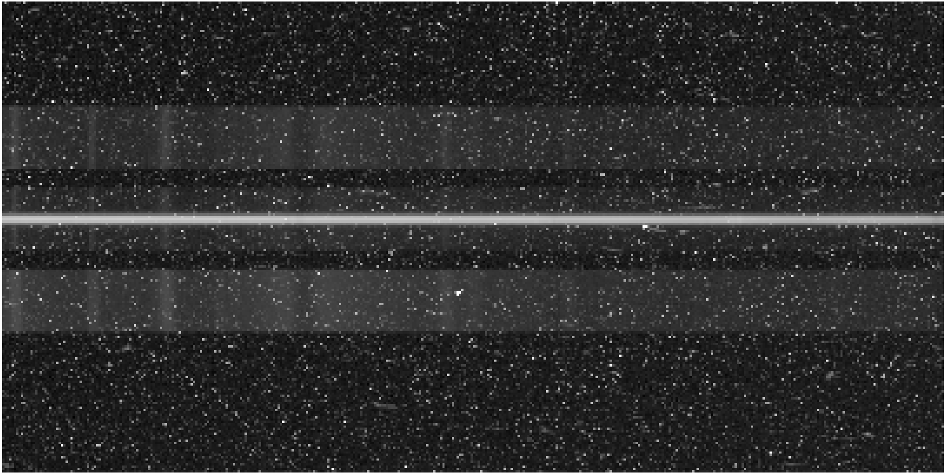


Figure: Science frame detail: 3600s exposure of BD+53 2790 (log scale).

Average frames

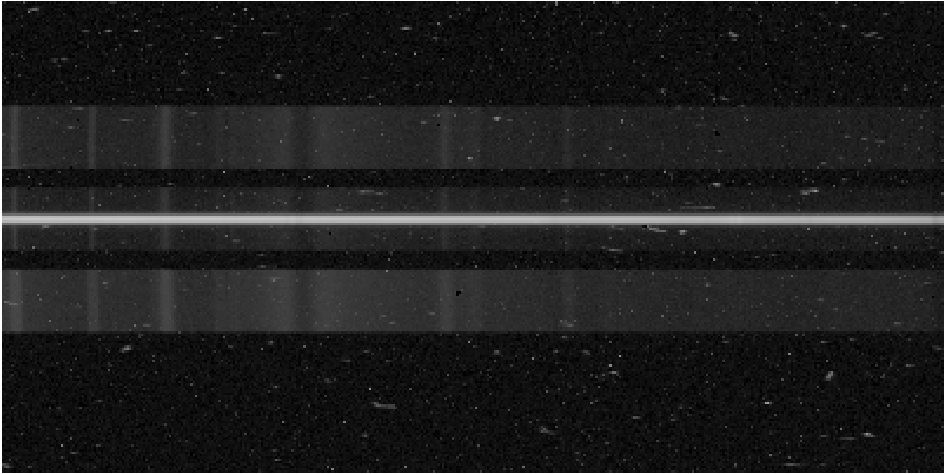


Figure: Science frame detail: dark frame subtracted.

Average frames

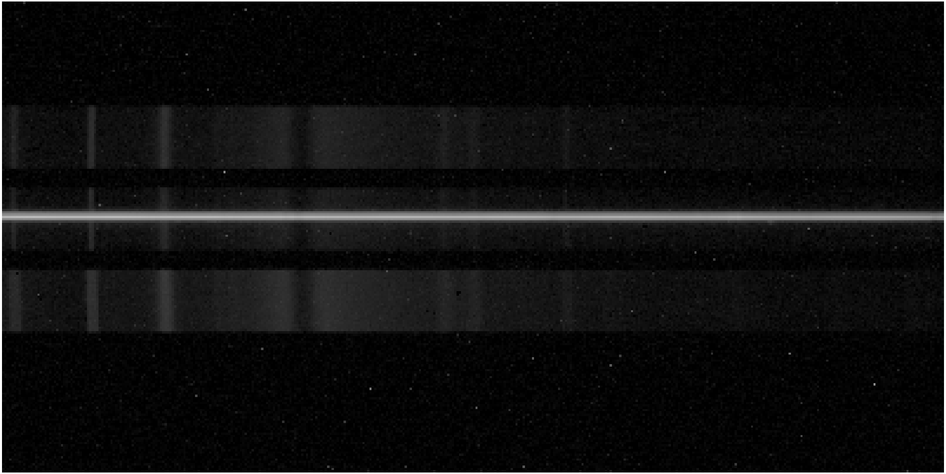
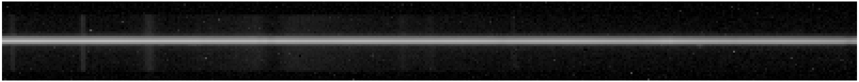


Figure: Science frame detail: dark frame subtracted, median of six exposures.

Sky background



Even the night sky is not completely black! Relevant for dark targets:

- air glow (emission lines due to chemical reactions in Earth's atmosphere, mainly at low altitudes $< 10^\circ$)
- scattered sunlight (astronomical twilight if Sun $< 18^\circ$ below horizon)
- moonlight
- *light pollution* (Potsdam, Berlin)
- in case of bad luck: planes (Tegel, Schönefeld)

Sky background

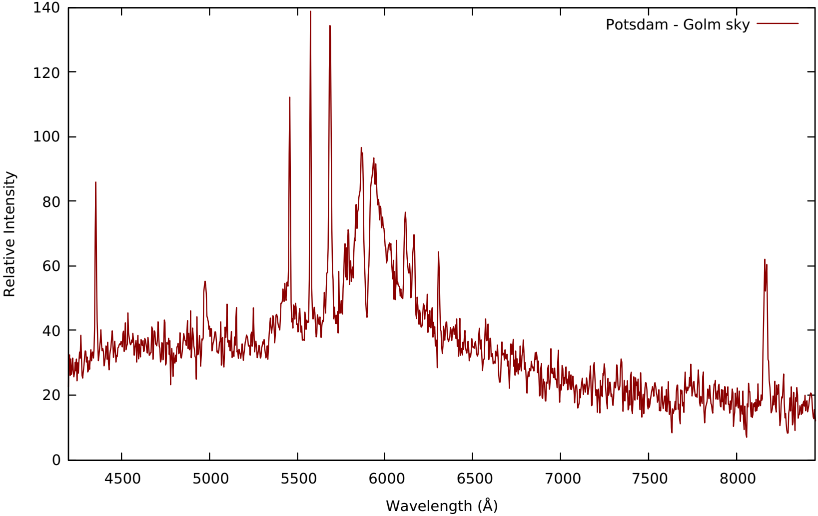


Figure: Potsdam sky background seen by DADOS (3h exposure average).

Sky background

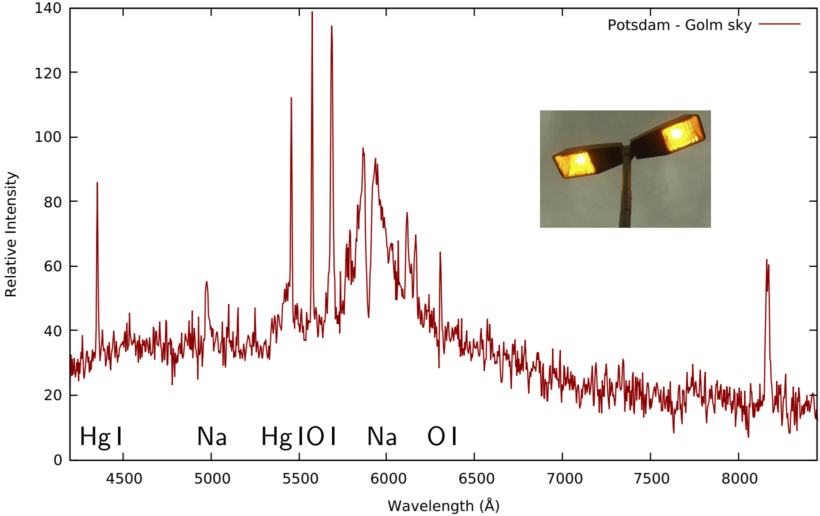


Figure: Potsdam sky background seen by DADOS (3h exposure average).

Dispersion relation

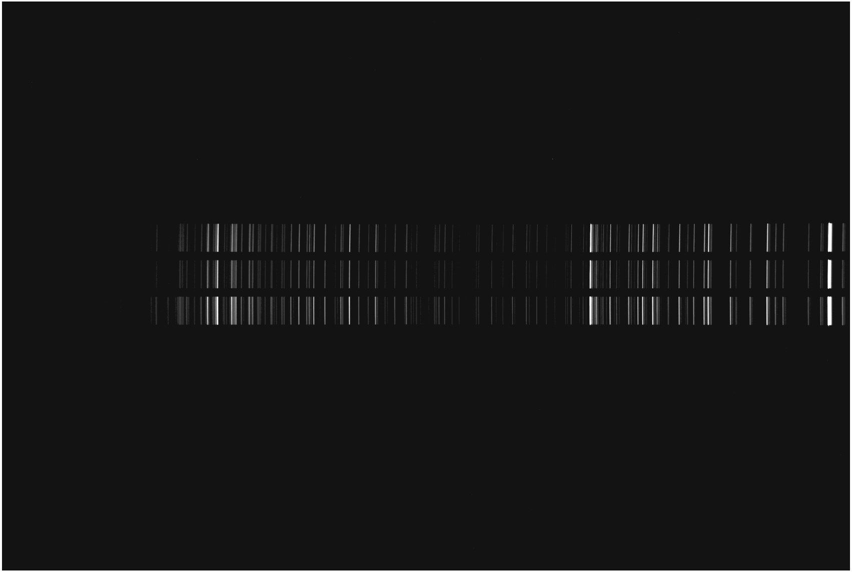


Figure: NeAr calibration frame.

Find dispersion relation

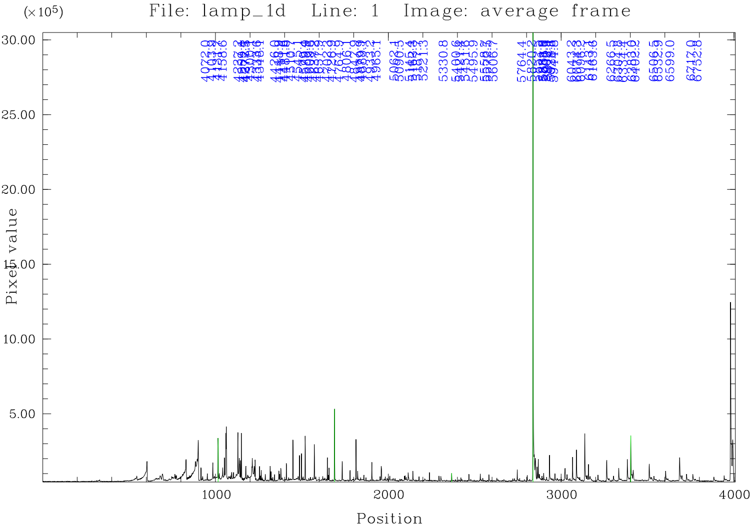


Figure: Semi-automatic emission line identification (NeXe lamp).

Find dispersion relation

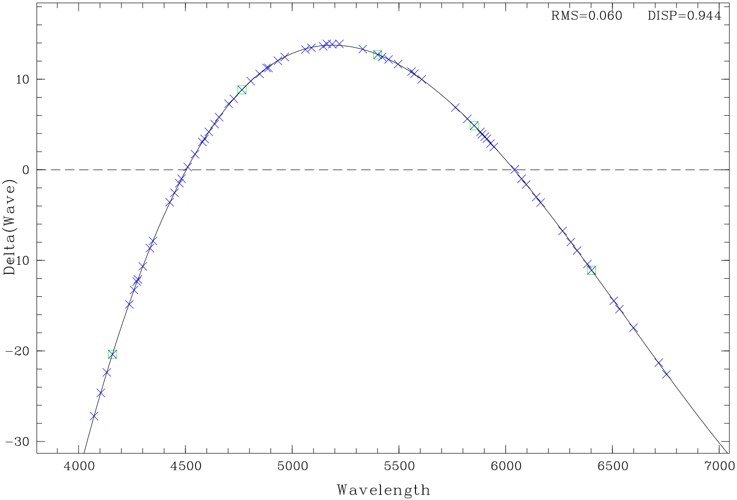
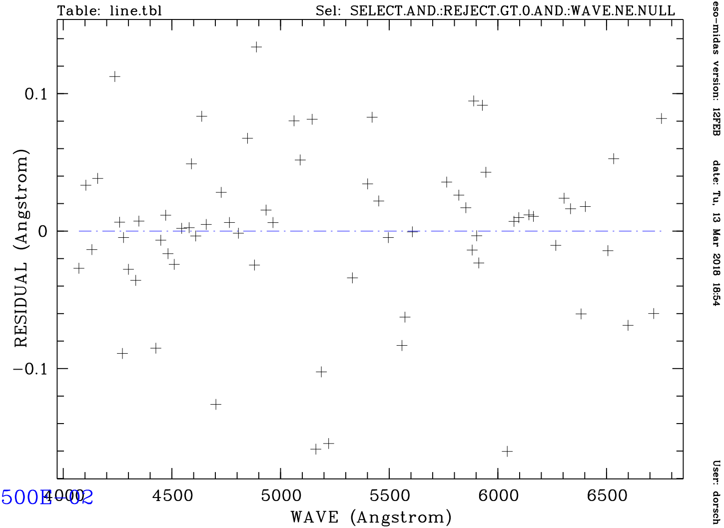


Figure: Dispersion relation as deviation from a linear relation between pixel and wavelength (NeXe lamp).

Find dispersion relation



: 6.07500E−02

Figure: Deviations from the fitted dispersion relation (NeXe lamp).

Step-by-step summary

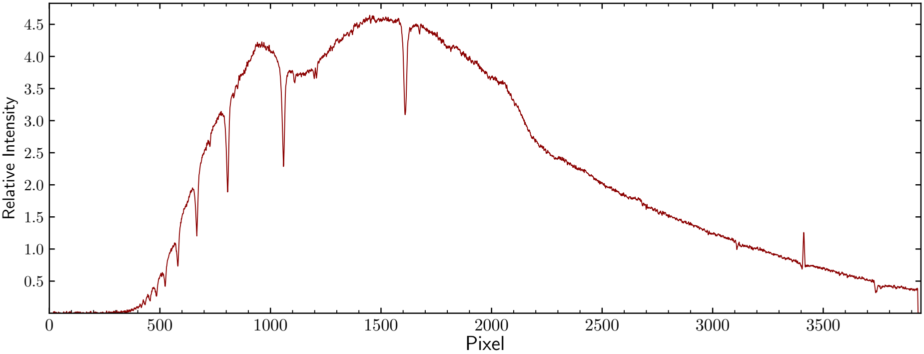


Figure: DADOS spectrum of Alcyone: dark, averaged.

Step-by-step summary

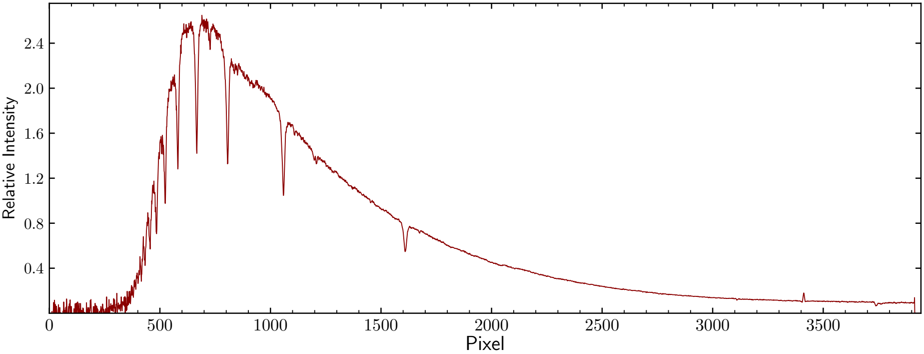


Figure: DADOS spectrum of Alcyone: dark, averaged, flat.

Step-by-step summary

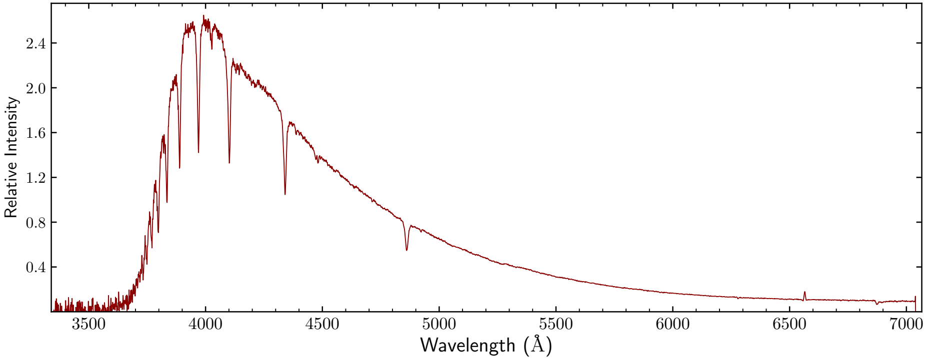


Figure: DADOS spectrum of Alcyone: dark, averaged, flat, calibrated.

Optional: (relative) flux calibration

Spectral shape is still affected by the flatfield shape, etc ...

+

We still don’t have physical units

Optional: (relative) flux calibration

To fix this, create a standard star:

- take spectrum of a laboratory source with known flux distribution $L(\lambda)$:

$$R_{\mathrm{lab}}(\lambda)$$

- then, the calibration factor is:

$$C(\lambda) = L(\lambda)/R_{\mathrm{lab}}(\lambda)$$

- take spectrum of a standard star (correct for atm. extinction!):

$$R_{\mathrm{std}}(\lambda)$$

- then, the flux of the std. star in physical units ($\mathrm{erg\,cm^{-2}\,s^{-1}\,\text{Å}^{-1}}$) is:

$$f_{\mathrm{std}}(\lambda) = C(\lambda) R_{\mathrm{std}}(\lambda) = \frac{R_{\mathrm{std}}(\lambda)}{R_{\mathrm{lab}}(\lambda)} L(\lambda)$$

Optional: (relative) flux calibration

If flux distribution of a standard (comparison) star $f_{\mathrm{std}}(\lambda)$ is known:

- take high S/N spectrum of standard star:

$$R_{\mathrm{std}}(\lambda)$$

- then, the "calibration" factor is:

$$c(\lambda) = f_{\mathrm{std}}(\lambda)/R_{\mathrm{std}}(\lambda)$$

- take spectrum of target star $R_*(\lambda)$, then:

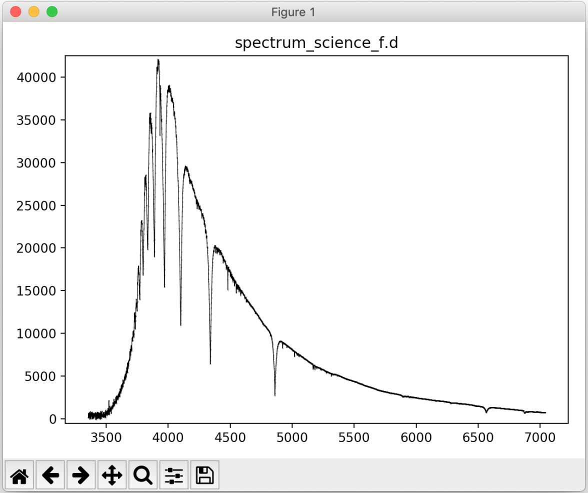
$$f_*(\lambda) = c(\lambda)R_*(\lambda) = \frac{R_*(\lambda)}{R_{\mathrm{std}}(\lambda)} f_{\mathrm{std}}(\lambda)$$

- the best calibrated star is Vega (no atm. extinction):

$$f_{\mathrm{Vega}}(5556\,\text{Å}) = 3.44 \pm 0.05\,\mathrm{erg\,cm^{-2}\,s^{-1}}\,\text{Å}^{-1}$$

Optional: (relative) flux calibration

Here, relative flux calibration using excellent synthetic spectra:



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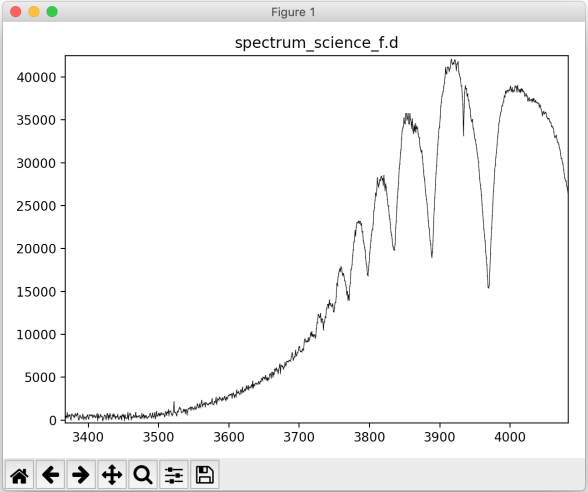

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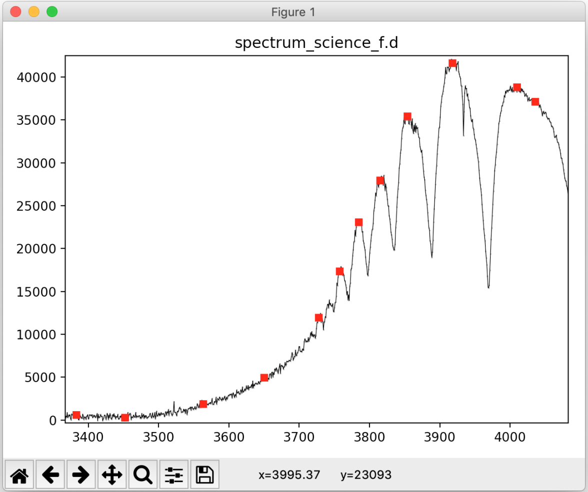

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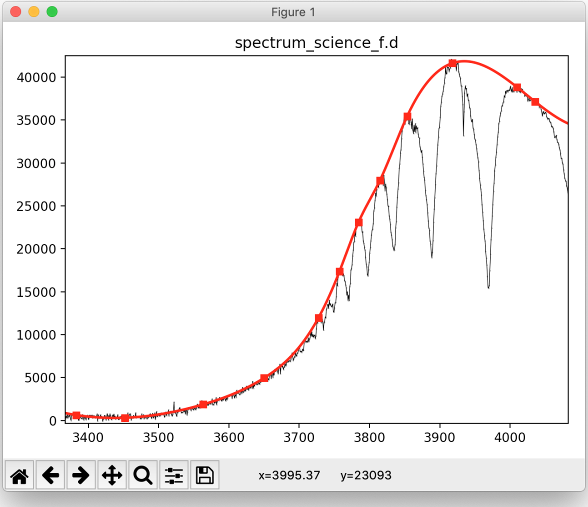

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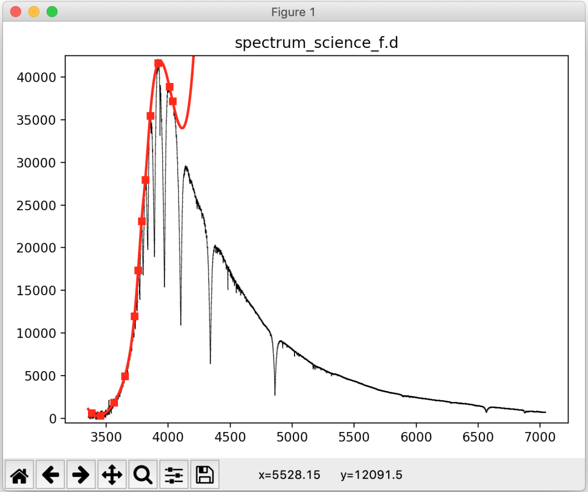

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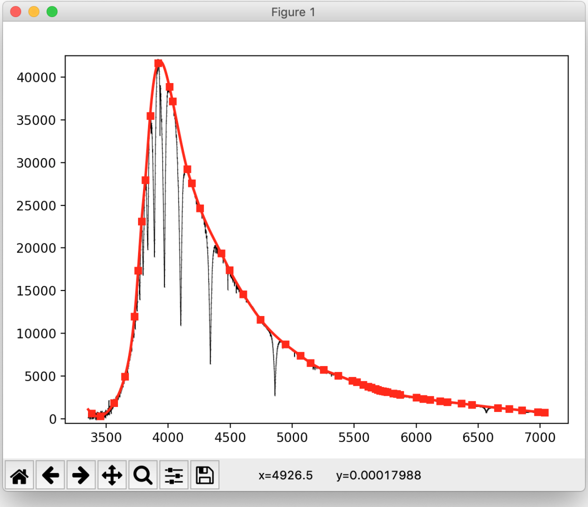
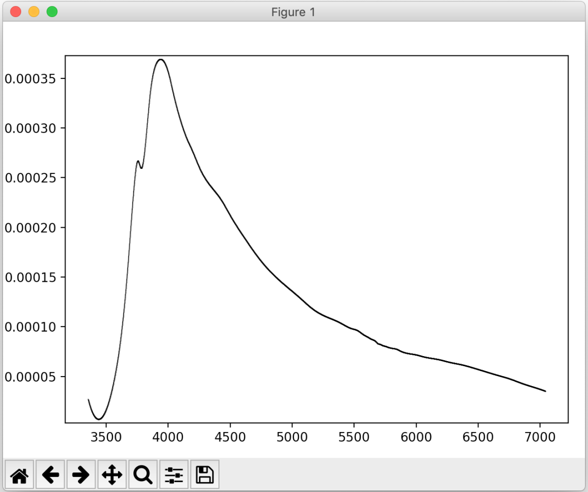


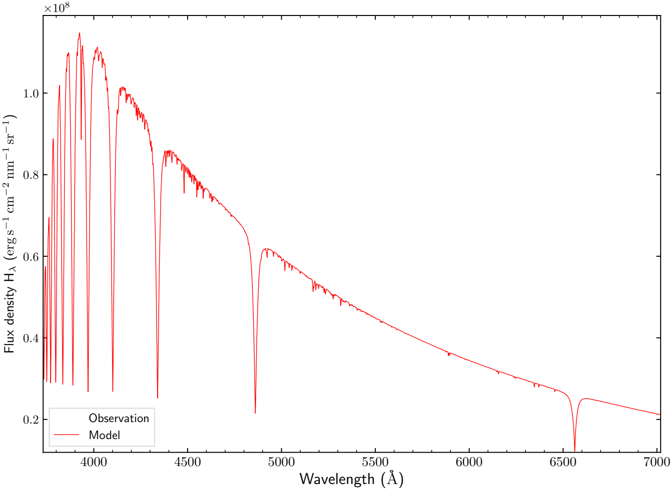
Optional: (relative) flux calibration

Here, relative flux calibration using excellent synthetic spectra:



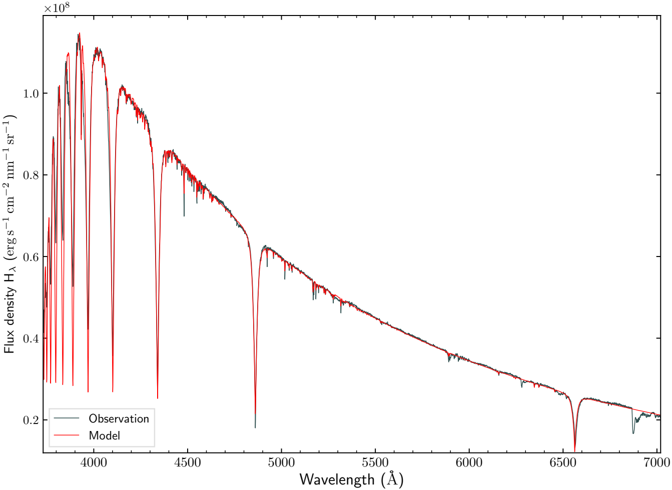
Optional: (relative) flux calibration

Here, relative flux calibration using excellent synthetic spectra:



Optional: (relative) flux calibration

Here, relative flux calibration using excellent synthetic spectra:



Why not absolute flux calibration?

Absolute flux calibration would be even better!
Fit synthetic spectra to get:

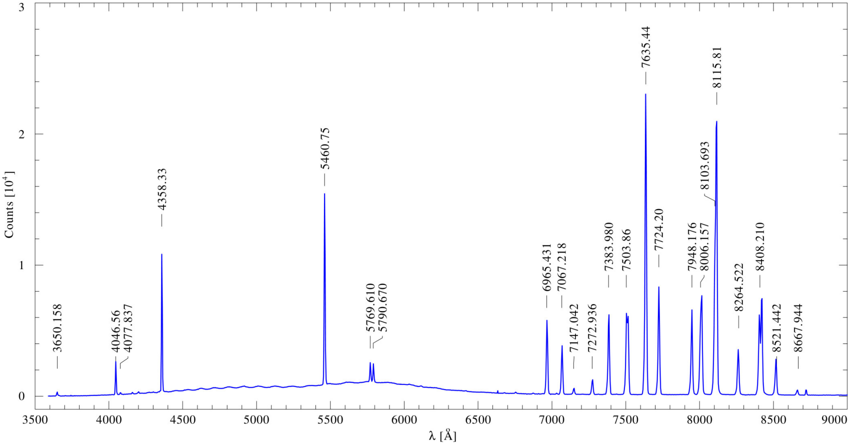
- angular diameter (solid angle) $\Theta = 2R/D$
- temperature $T_{\rm eff}$
- color excess (interstellar reddening) $E_{\rm B-V}$
- using parallax ϖ → stellar radius $R = \Theta/(2\varpi)$

Problems:

- airmass changes with distance to horizon
  → wavelength dependent extinction
- star may leave the slit during the observation
- clouds

Optional: determine resolution with calibration lamp

We need to know the spectral resolution to fit spectra!



Arc lines are intrinsically sharp → fit Gaussian: $R = \lambda_{\mathrm{line}}/\mathrm{FWHM}_{\mathrm{line}}$.

Example reduction using python scripts

In three steps (adjust file names, run scripts with -h for help):

```
# stack hgar images and flat images for star
~/scripts/evolved/0_average_images.py  hgar/ -o
   star_hgar_stacked.fit

# identify calibration lines
~/scripts/evolved/1_findcaliblines.py  -arc
   star_hgar_stacked.fit -rsc 500 570

# apply calibration and extract spectra
~/scripts/evolved/2_extractspectrum.py -sc
   star_1200s_stacked.fit -df ~/data/20190903/dark
   /1200s/ -ff flats/ -fd ~/data/20190903/dark/1s/
    -rsc 500 570
```

Questions?