Lecture on spectroscopy and applications (Brno 02.09.15)

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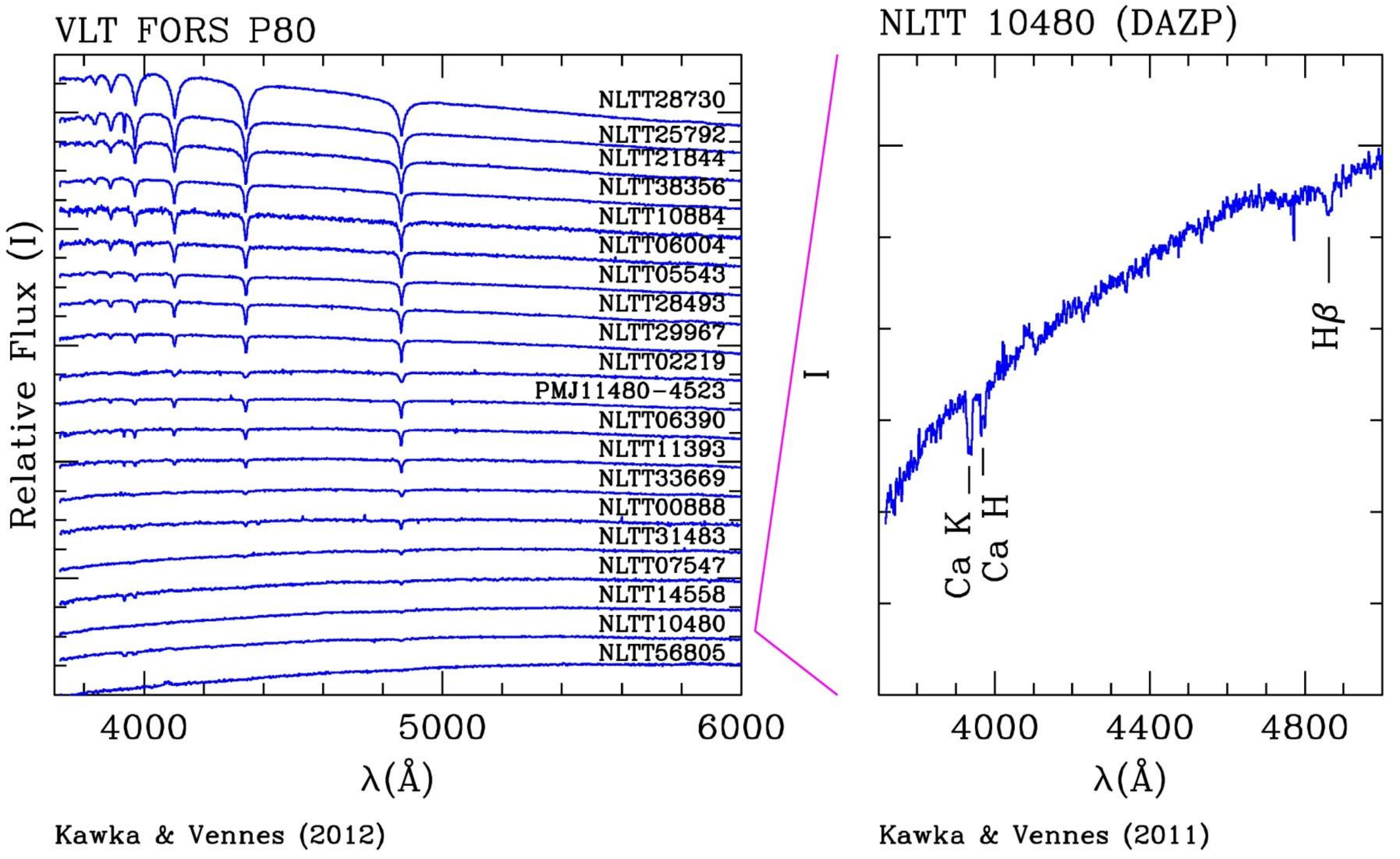
Syllabus:

- Physical description:
  - Atoms and molecules; light properties-energy and polarization: Temperature, magnetic and abundance effects.
  - Spectrographs; basic concepts.
  - Explore some astrophysical contexts.
- Instrumental capabilities:
  - Wavelength range and resolving power; integral field; echelle.
  - Multi-wavelength astrophysics from the ultraviolet to the infrared (IR).
- With examples and applications.

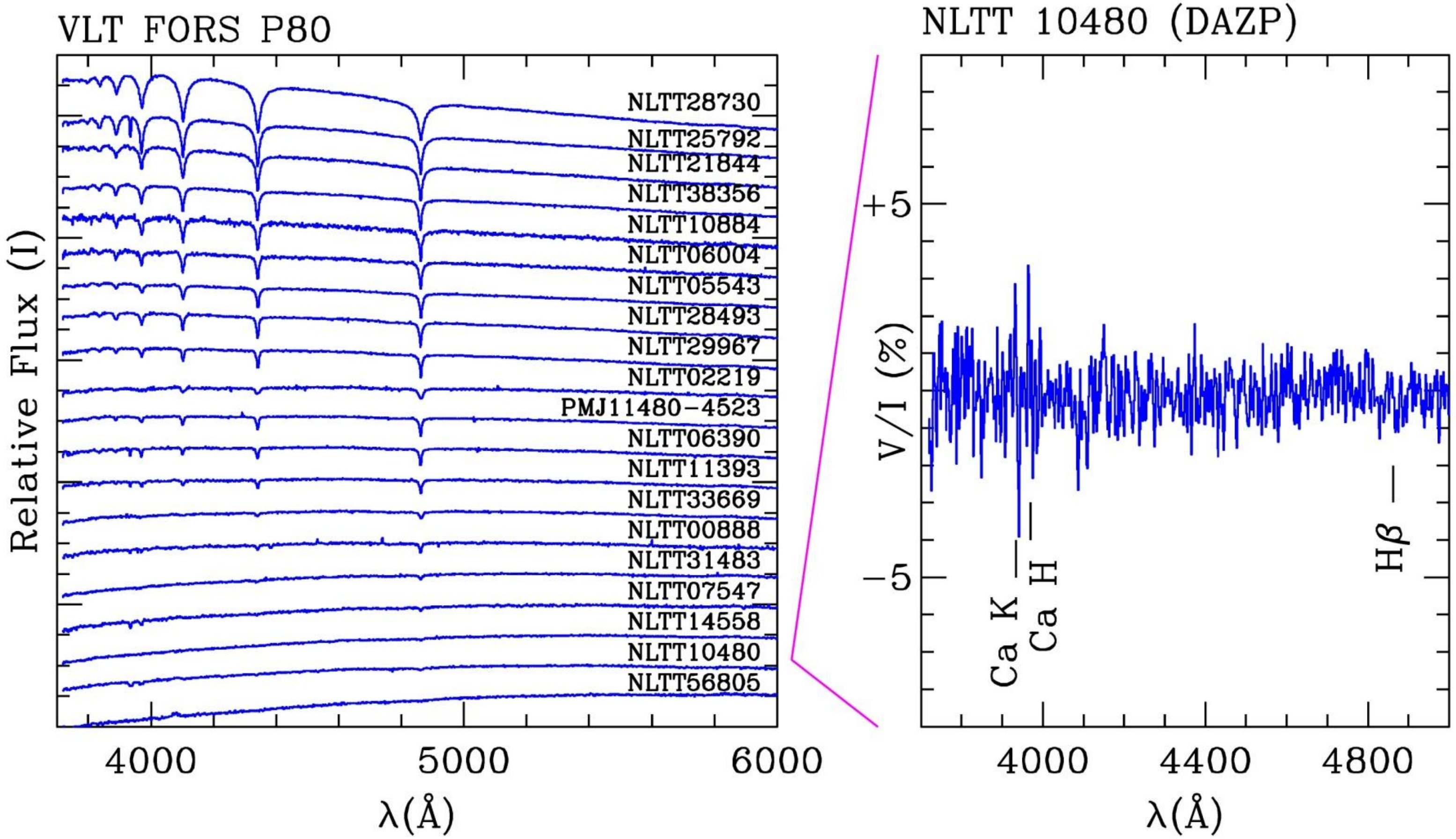
Physics 1.1 Temperature, Z, **B**

- In the following we will use white dwarf properties to illustrate some physical properties of stars.
- White dwarfs are compact stars with a fully degenerate core (C, O, Ne, ?). However, their atmospheres exhibit a range of ``classical'' phenomena.
- Temperature effects as in OBA stars, but with more extreme abundance variations, and stronger magnetic fields (kG to GG).
- Surface abundance ranges from pure H, He, to C and O with extreme metallicity variations.

Physics 1.2 Temperature, Z, **B**



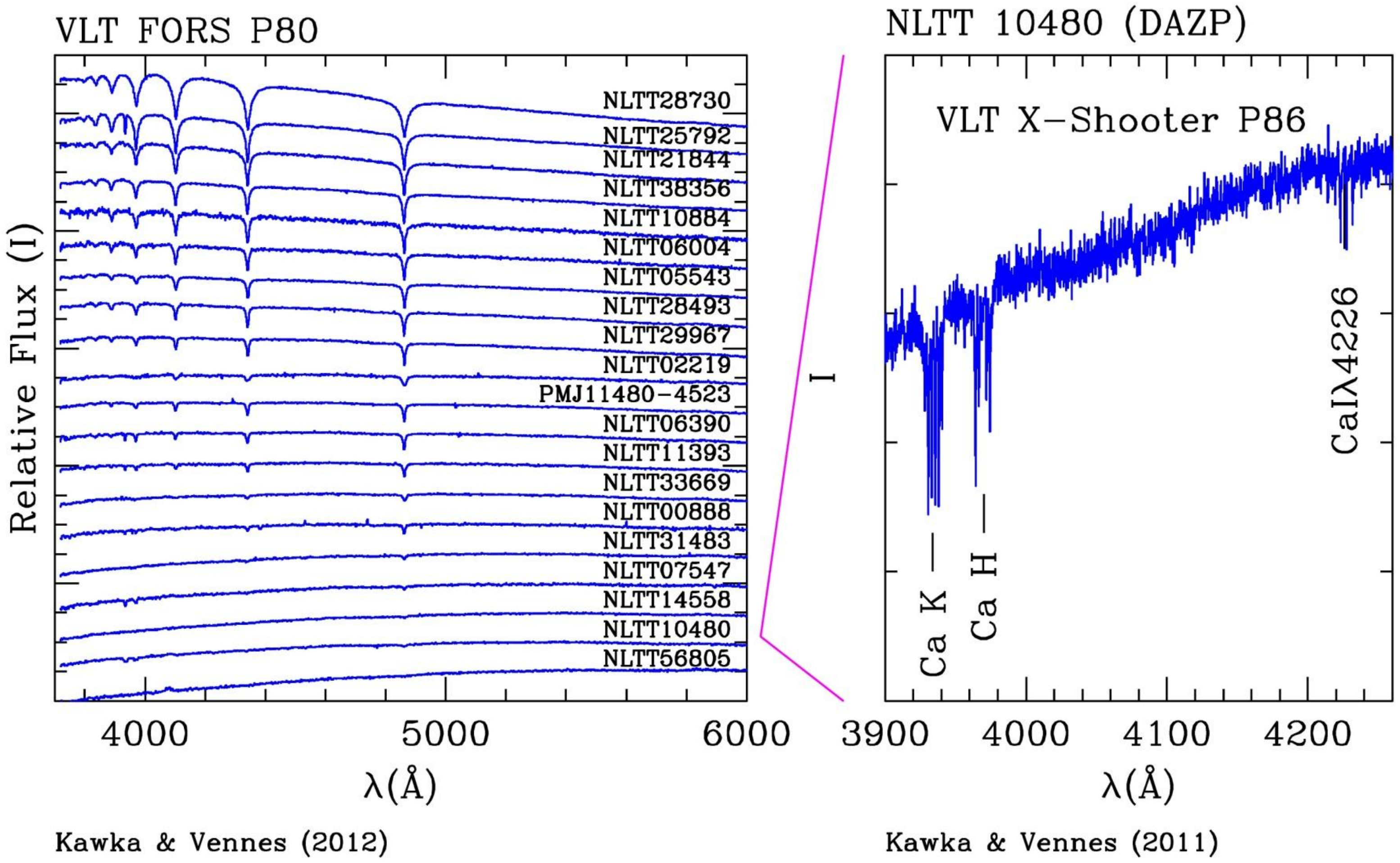
Physics 1.3 Temperature, Z, **B**



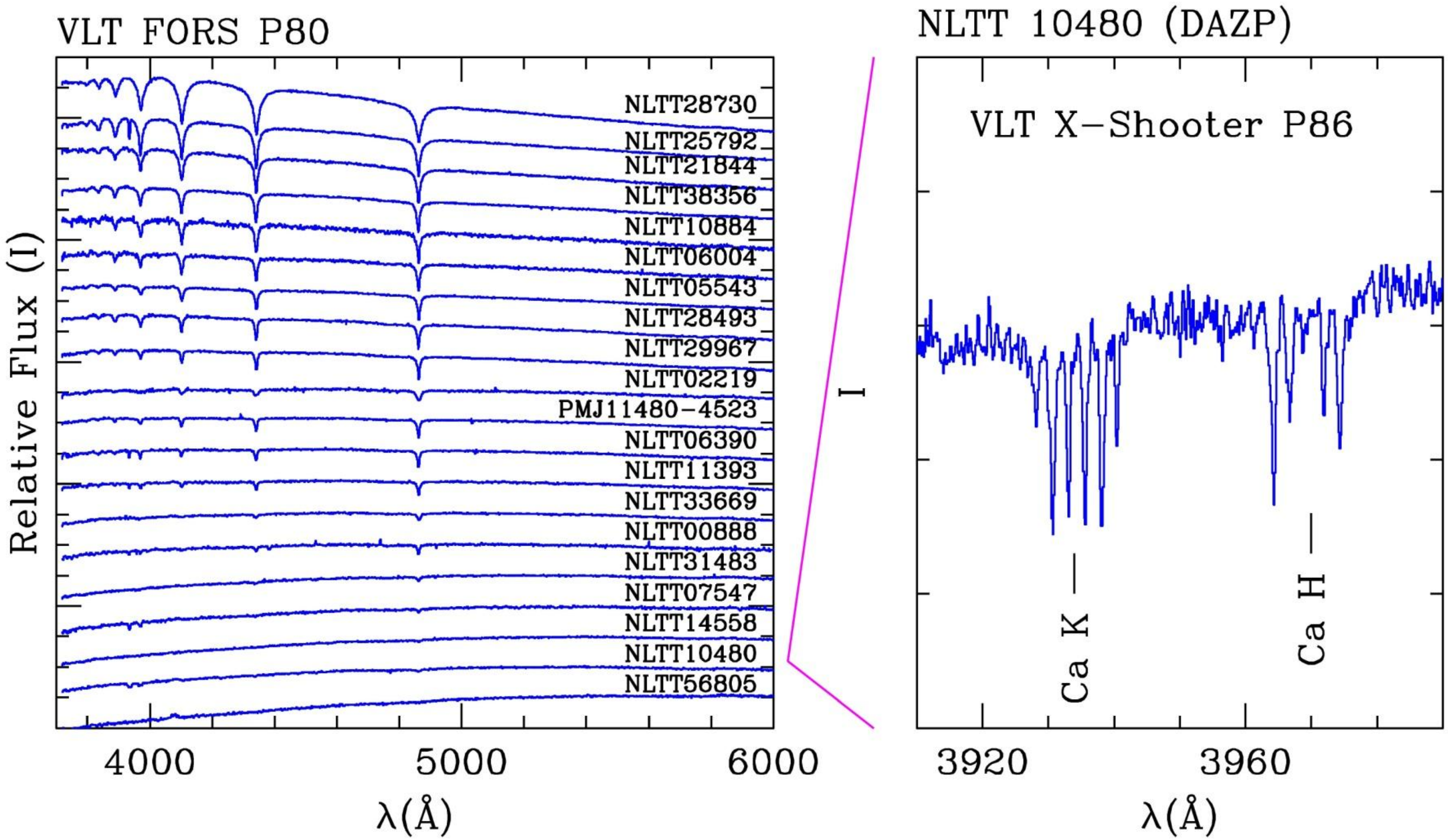
Kawka & Vennes (2012)

Kawka & Vennes (2011)

Physics 1.4 Temperature, Z, **B**



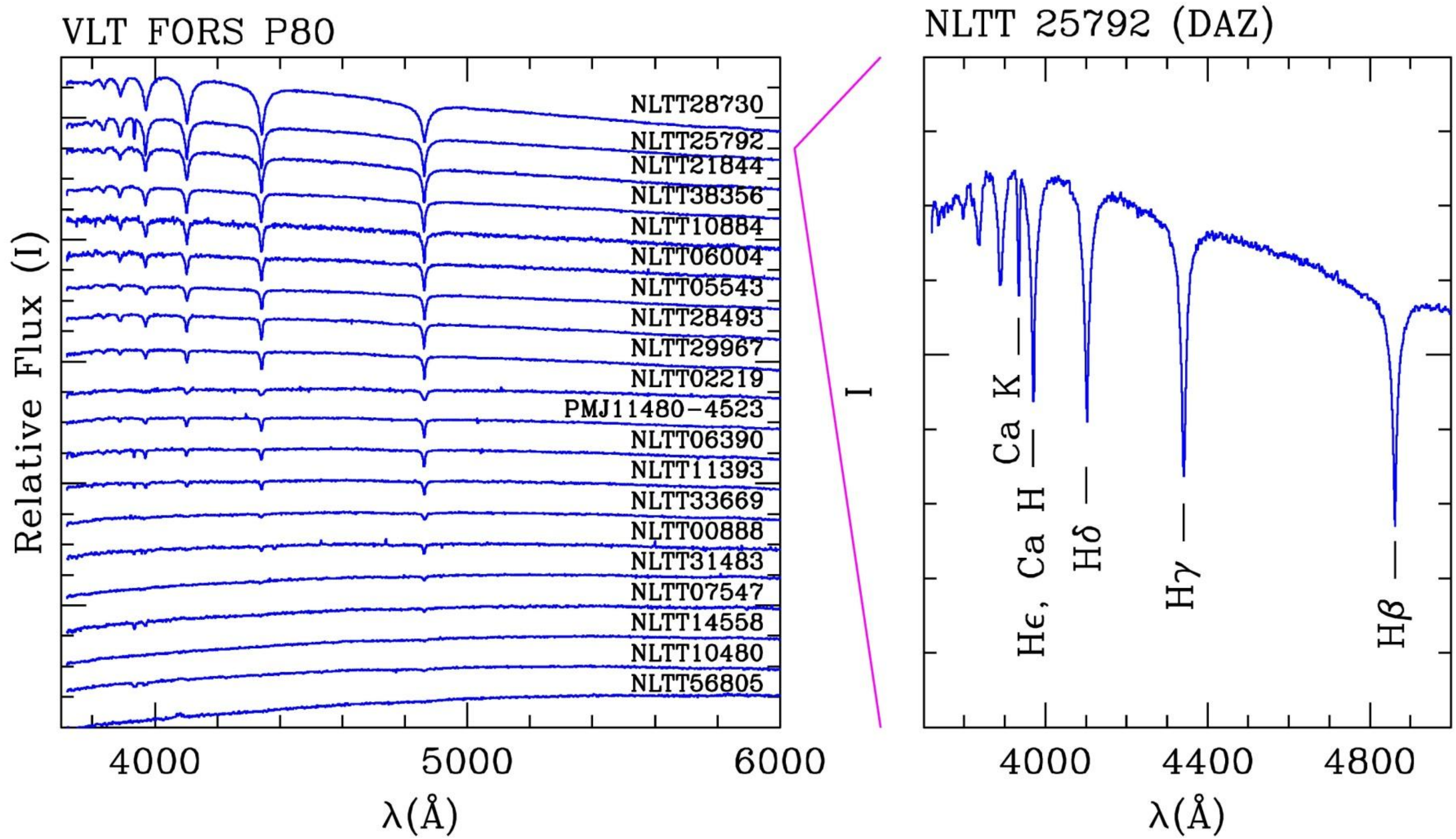
Physics 1.5 Temperature, Z, **B**



Kawka & Vennes (2012)

Kawka & Vennes (2011)

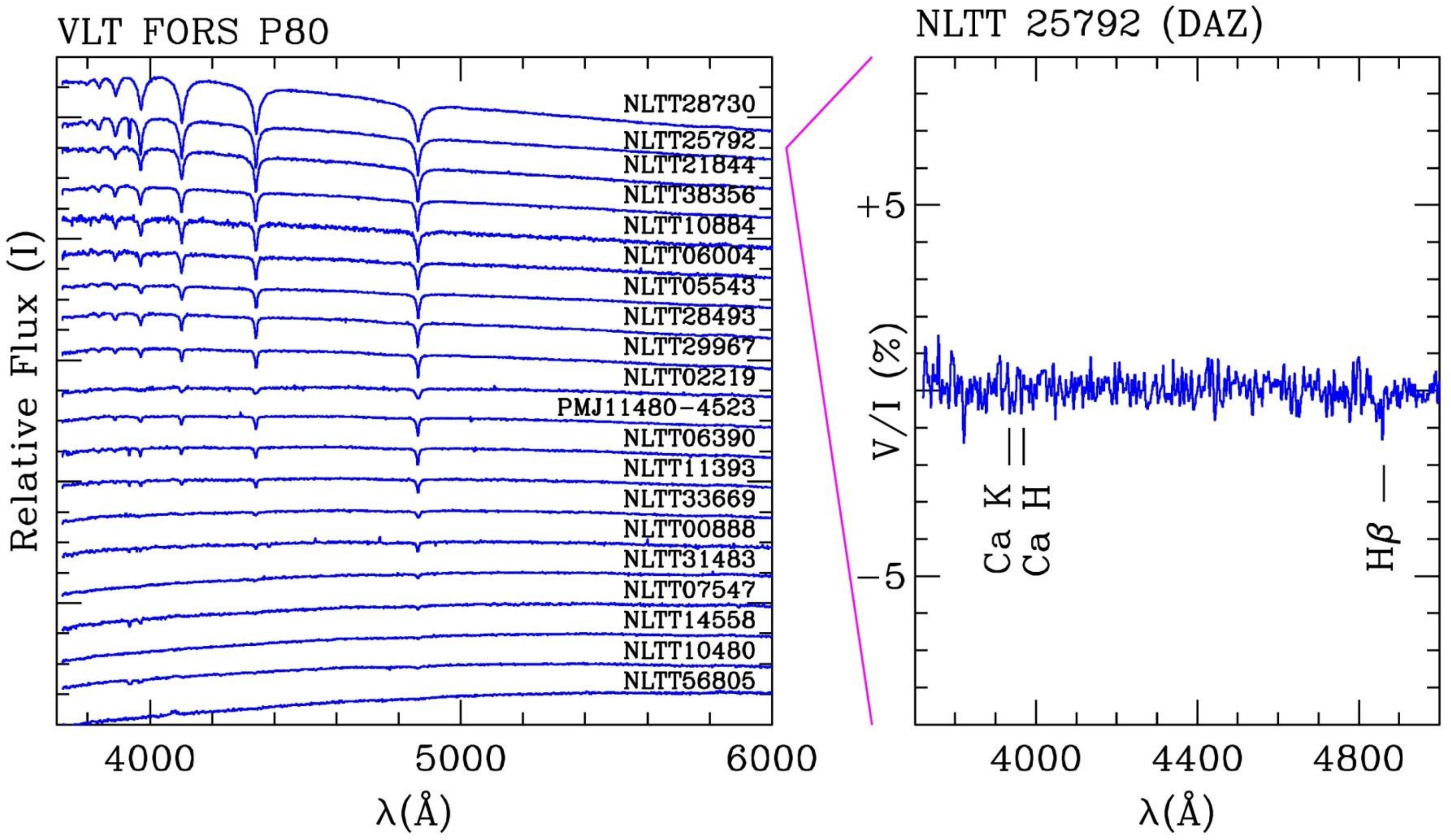
Physics 1.6 Temperature, Z, **B**



Kawka & Vennes (2012)

Vennes & Kawka (2013)

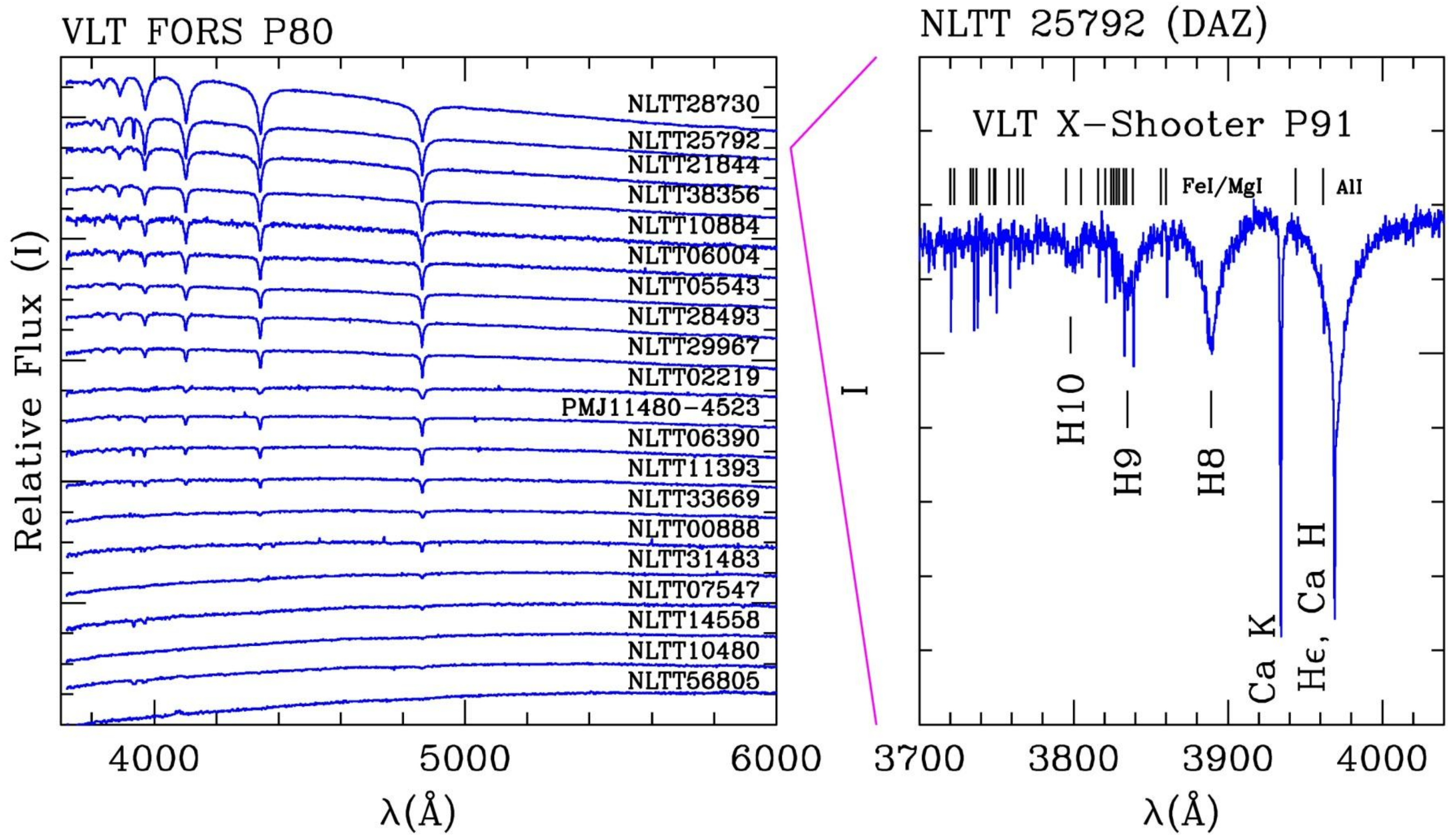
Physics 1.7 Temperature, Z, **B**



Kawka & Vennes (2012)

Kawka & Vennes (2012)

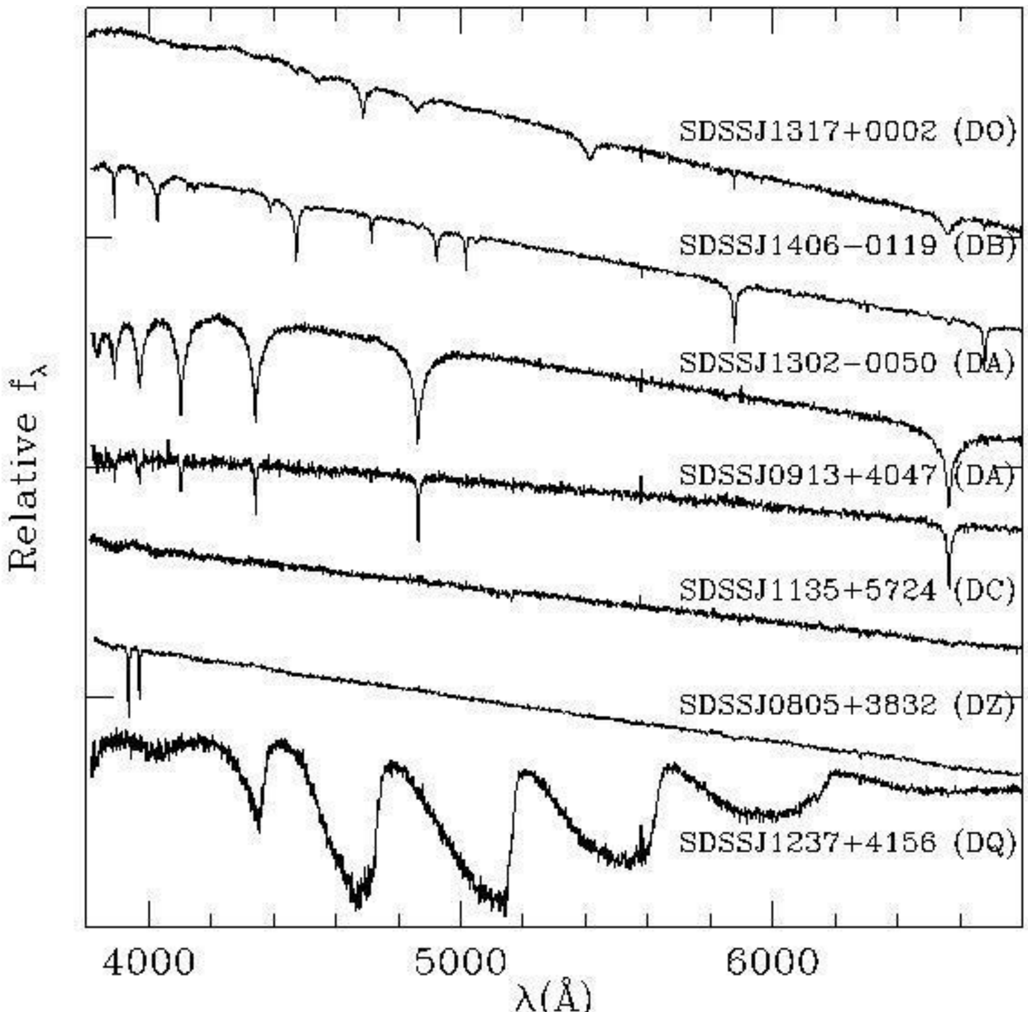
Physics 1.8 Temperature, Z, **B**



Kawka & Vennes (2012)

Vennes & Kawka (2013)

Physics 1.9 Temperature, Z, **B**



DO: HeII lines

DB: HeI lines

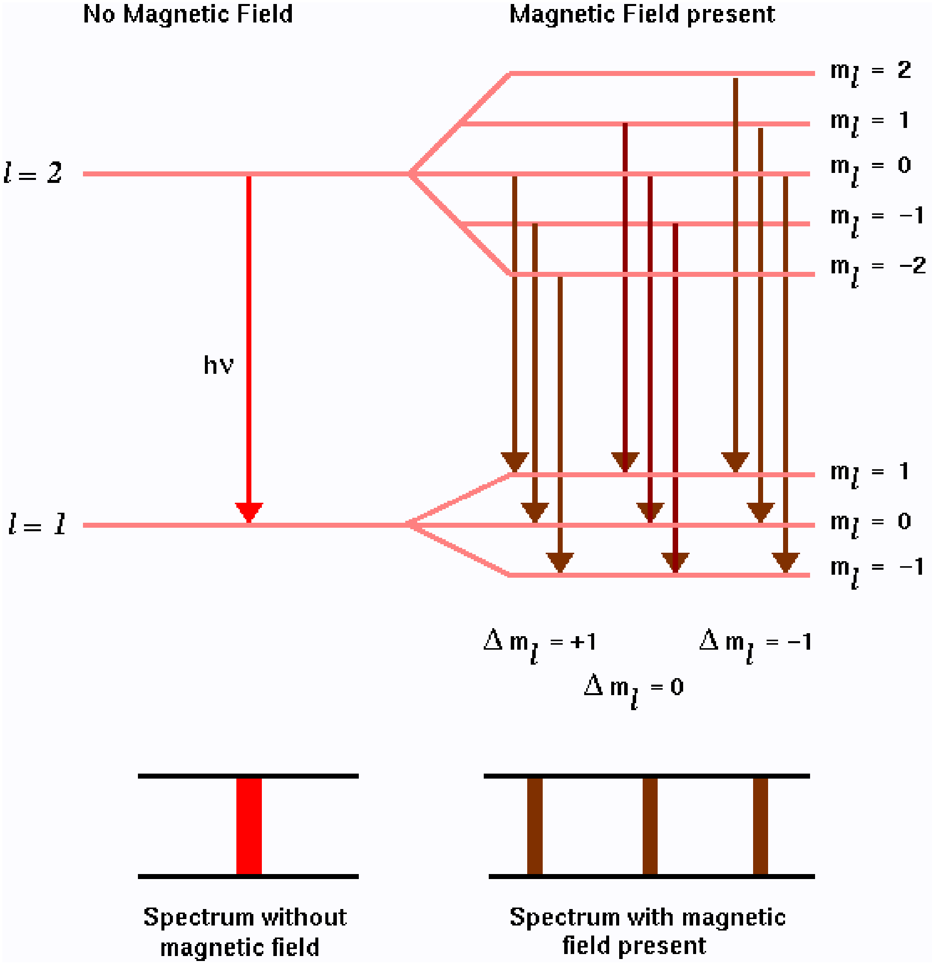
DA: strong to weak HI lines

DC: weak to no HeI lines

DZ: weak to no HeI lines but metal lines

DQ: weak to no HeI lines but C2/CN/CH molecular vibrational bands

Physics 2.1 Zeeman effect



l = angular momentum

m_l = magnetic moment:

$$m_l = -l, -l+1, \ldots, 0, \ldots, l-1, l$$

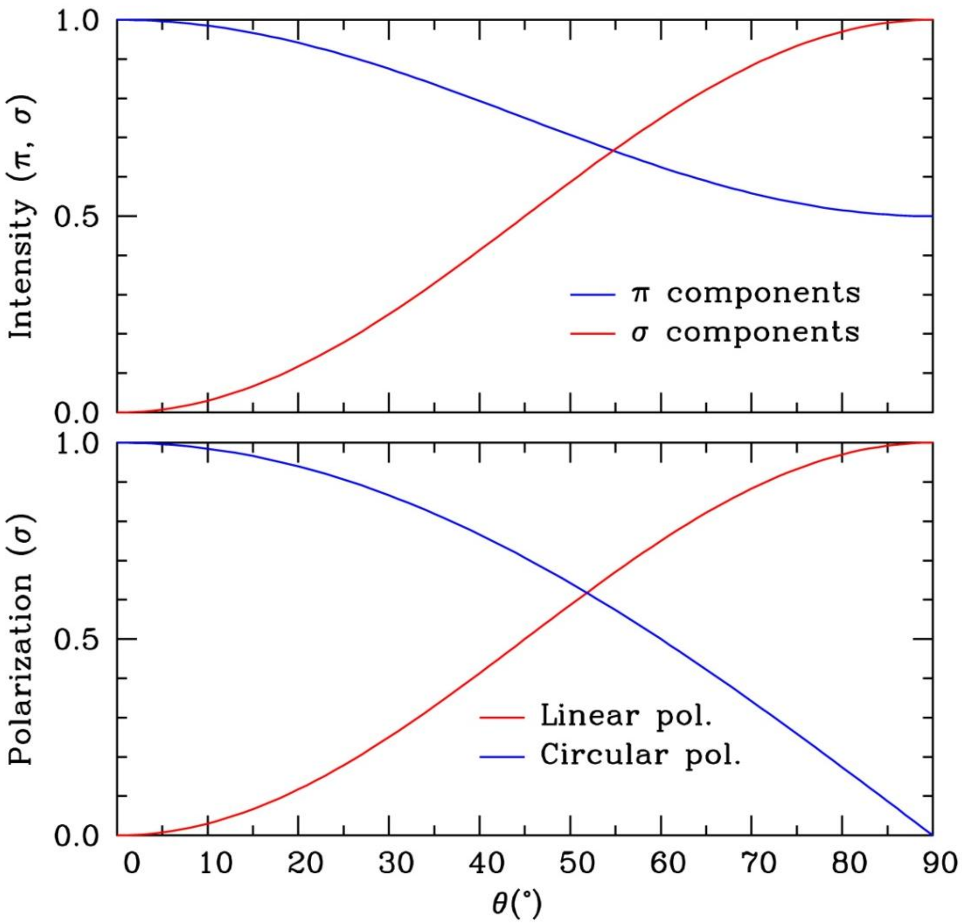
The allowed transitions follow the selection Δm_l=0,±1

In this example, the Zeeman triplet (normal Zeeman) splits at:

$$\Delta\lambda_B = 4.67\times10^{-7}\lambda^2 B_s(g_i m_i - g_j m_j)$$

Where i/j are lower/upper levels. B_s is mean surface B.

Physics 2.2 Zeeman effect



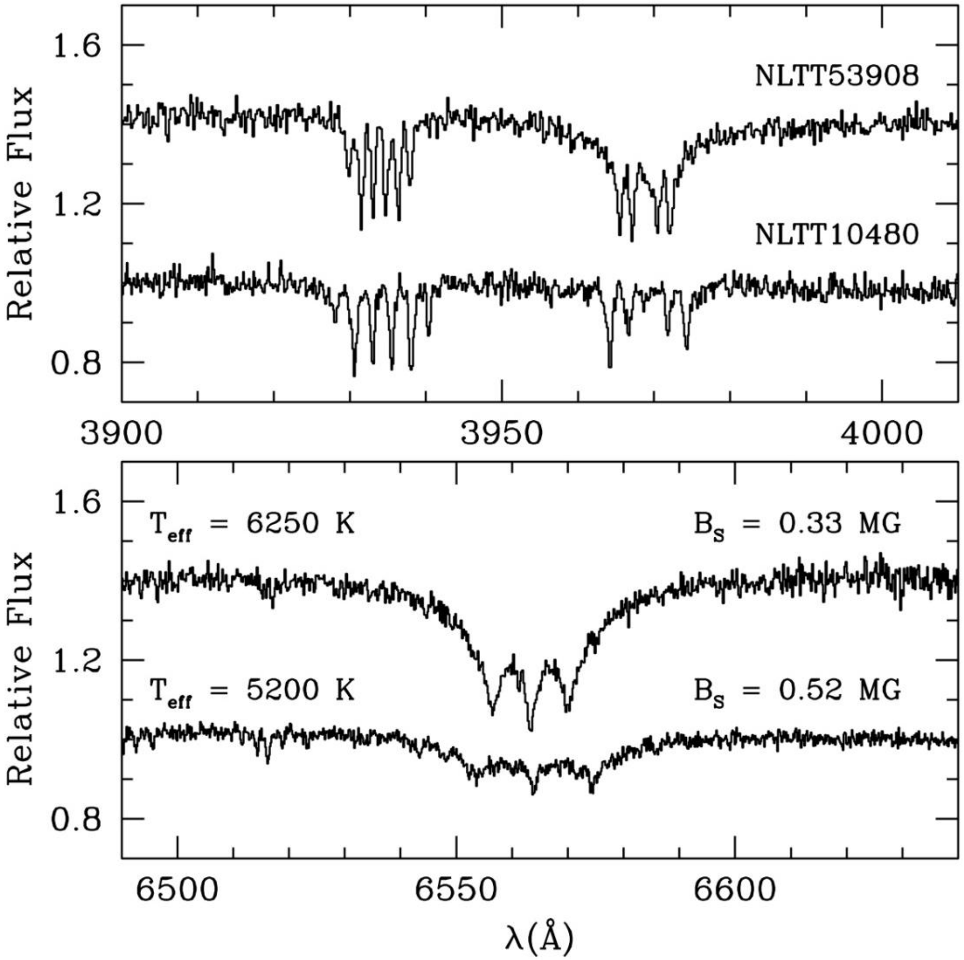
Observed behaviour:

The line intensity (π and σ)in absorption) and polarization (σ) depends on viewing angle (to field orientation):

The σ components are at maximum intensity at 90° with nil circular polarization and full linear polarization.

The contrast between σ and π intensity constrains a key geometric parameter, the field inclination relative to viewer.

Physics 2.3 Zeeman effect

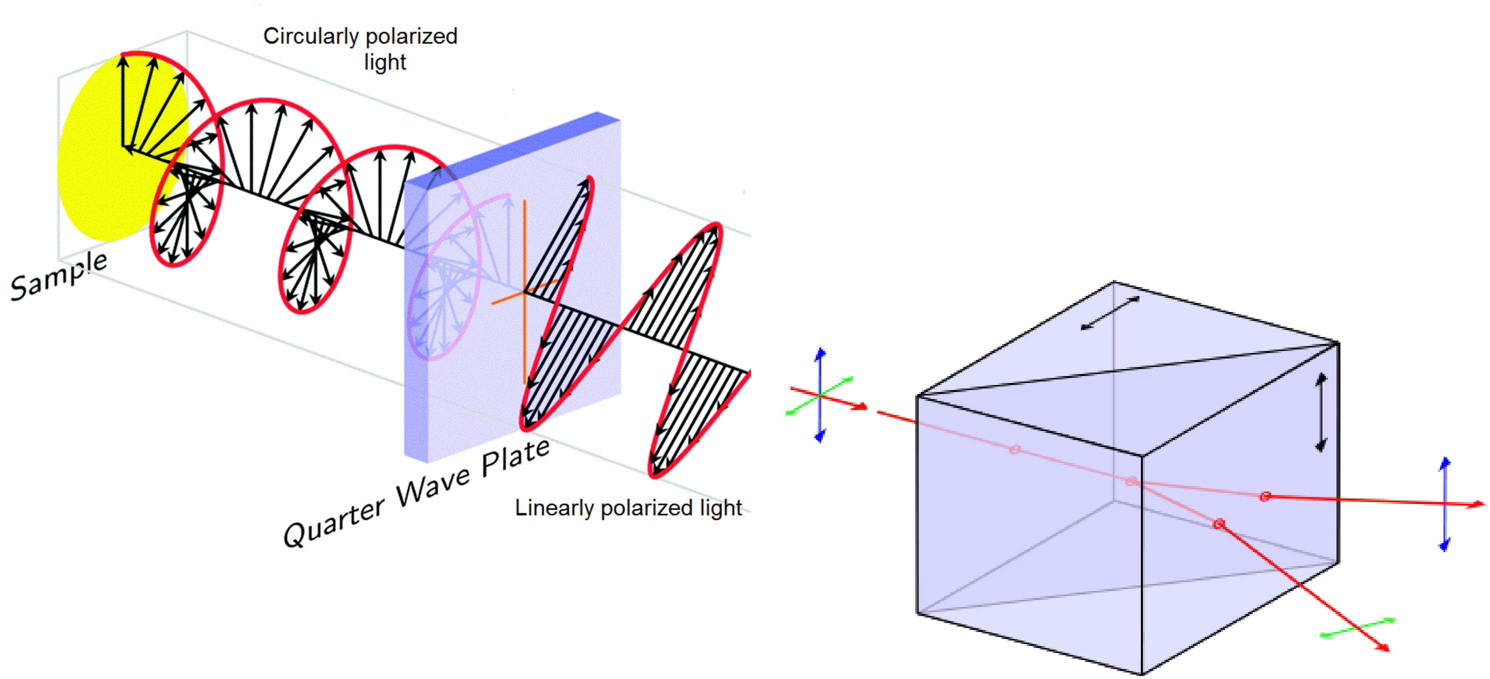


Intermediate-dispersion spectroscopy ESO VLT/Xshooter:

NLTT 53908 (2 Gyr) and NLTT10480 (4 Gyr) are two magnetic *and* polluted white dwarfs. High incidence of magnetism in this class of objects (33%) suggests that all old white dwarfs are magnetic.

CaH&K show *anomalous* Zeeman effect: quadruplet and sextuplet, 4 and 6 discrete values for $(g_i m_i - g_j m_j)$ instead of 3.

Physics 2.4 Zeeman effect



Basic configuration for the measurement of circularly polarized light:

$$\frac{V}{I} = \frac{1}{2}\left[\left(\frac{f^{o} - f^{eo}}{f^{o} + f^{eo}}\right)_{\theta=+45} - \left(\frac{f^{o} - f^{eo}}{f^{o} + f^{eo}}\right)_{\theta=-45}\right]$$

Spectroscopy 1.1

- The main ingredients of spectroscopy:
  1. *F*(λ): The intrinsic (model or template) astrophysical intensity spectrum measured at Earth (star, galaxies, HII regions, any source),
  2. *I*(λ): The instrument response (sensitivity or throughput, and instrument profile or resolution, slit loss ...),
  3. *T*(λ): Atmospheric transmittance,
  4. Other astrophysical effects might require special attention such as stellar rotation G(λ).
  5. For example assuming a non-rotating stellar model *F*(λ), the observed count spectrum of a rotating star is the result of the convolution:

$$C(\lambda) = [T(\lambda)F(\lambda)] * G(\lambda) * I(\lambda)$$

Spectroscopy 1.2

- Mathematical convolution applied to rotation:

$$F(\lambda) = F * G = \int_{\lambda-\Delta\lambda_L}^{\lambda+\Delta\lambda_L} F(\lambda')G(\lambda'-\lambda)d\lambda'$$

Where $\Delta\lambda_L$ is calculated at maximum velocity (edge of stellar disc ... next slide).

- And applied to the instrument profile:

$$C(\lambda) = F * I = \int_0^{\infty} F(\lambda')I(\lambda'-\lambda)d\lambda'$$

Where it is sufficient to integrate such that $|\lambda-\lambda'| >> \Delta\lambda$ and $\Delta\lambda$ is the instrumental resolution (studied next).

- ...and remember convolution is commutative and associative ...

Spectroscopy 1.3

- Measurement of stellar rotation is a major application of astrophysical spectroscopy. In the convolution integral

$$F(\lambda) = F * G = \int_{\lambda-\Delta\lambda_L}^{\lambda+\Delta\lambda_L} F(\lambda')G(\lambda'-\lambda)d\lambda'$$

$G(\lambda'-\lambda)$ is given by Gray (1976, 1992, 2005, 2008):

$$G(\Delta\lambda = \lambda' - \lambda) = c_1[1-(\Delta\lambda/\Delta\lambda_L)^2]^{1/2} + c_2[1-(\Delta\lambda/\Delta\lambda_L)^2]$$

Where $\Delta\lambda_L$ is the largest observed wavelength shift at the surface of a star rotating at a projected velocity *v* sin(*i*):

$$\Delta\lambda_L = \frac{\lambda}{c} v\sin(i)$$

In observing stellar spectra, a measurement of *v*sin(*i*) is one of the results hoped for...

Spectroscopy 1.4

- Measurement of stellar rotation:

The parameters c_1 and c_2 contain a major physical ingredient, the limb-darkening coefficient ε ... The intensity of emitted light decreases from centre to limb (see Mihalas 1978, Stellar Atmospheres). In

$$G(\Delta\lambda = \lambda' - \lambda) = c_1[1-(\Delta\lambda/\Delta\lambda_L)^2]^{1/2} + c_2[1-(\Delta\lambda/\Delta\lambda_L)^2]$$

$$c1 = \frac{2(1-\varepsilon)}{\pi(1-\varepsilon/3)}, c2 = \frac{\varepsilon}{2(1-\varepsilon/3)}$$

A value ε=0 corresponds to a uniformly illuminated disc and ε=0.6 is a representative empirical and theoretical value with the limb 60% darker than the centre.

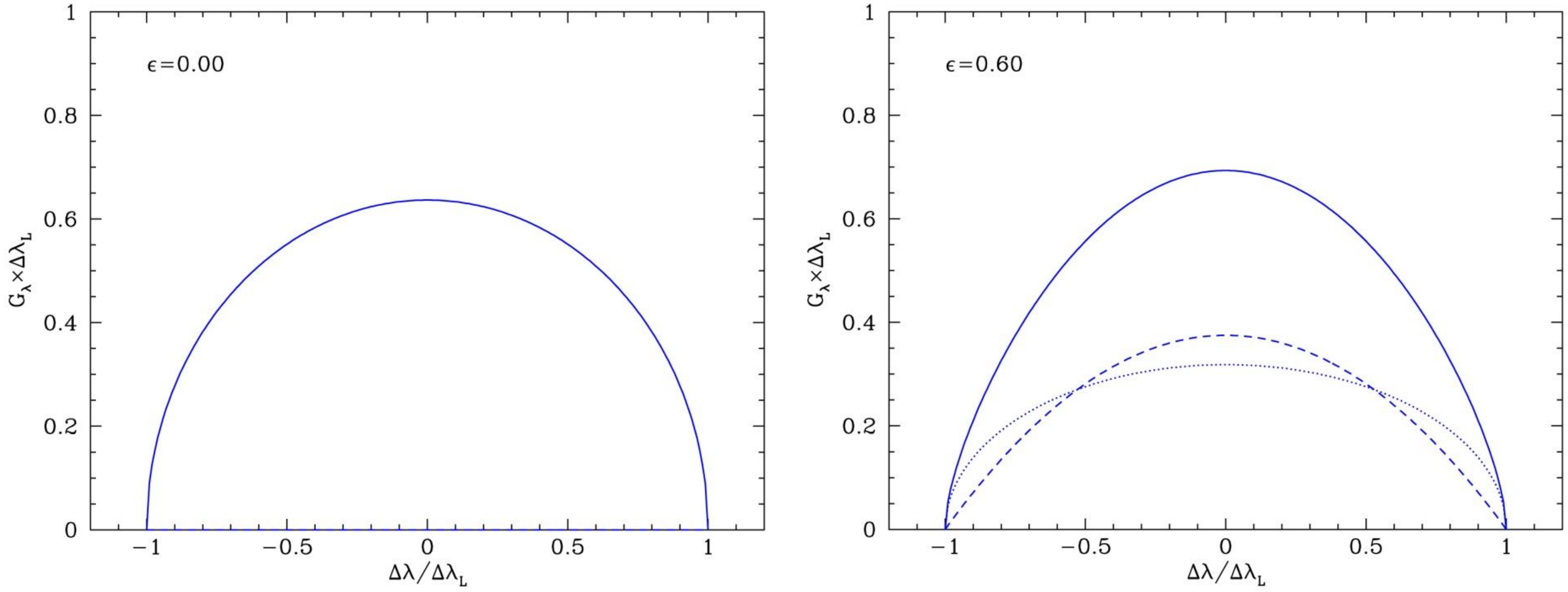
The next slide displays the function *G* in terms c_1 and c_2.

Spectroscopy 1.5

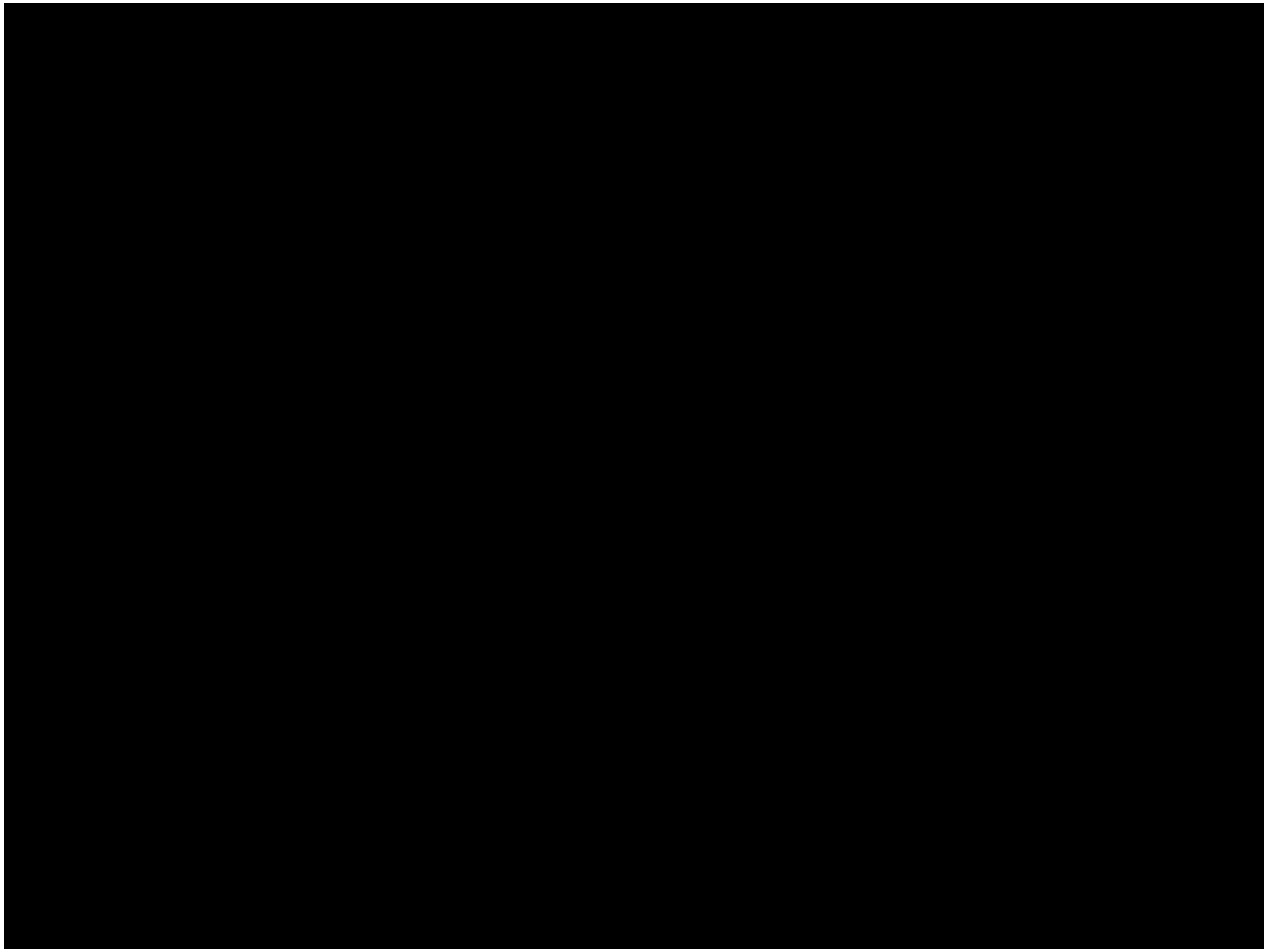
- Measurement of stellar rotation:

$$G(\Delta\lambda = \lambda' - \lambda) = c_1[1-(\Delta\lambda/\Delta\lambda_L)^2]^{1/2} + c_2[1-(\Delta\lambda/\Delta\lambda_L)^2]$$

$$c_1 = \frac{2(1-\varepsilon)}{\pi(1-\varepsilon/3)}, c_2 = \frac{\varepsilon}{2(1-\varepsilon/3)}$$



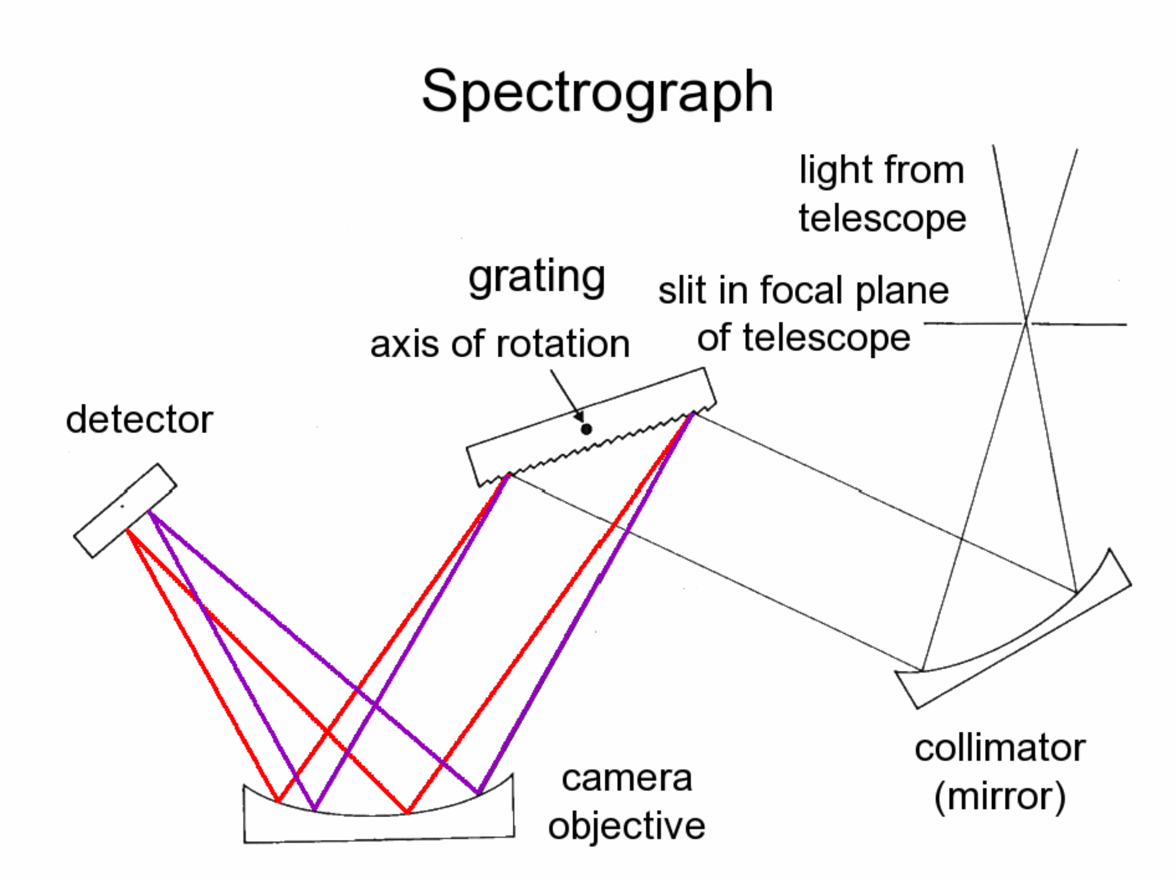
Spectroscopy 1.6 -G(λ) movie



Spectroscopy 1.7 -CaK movie

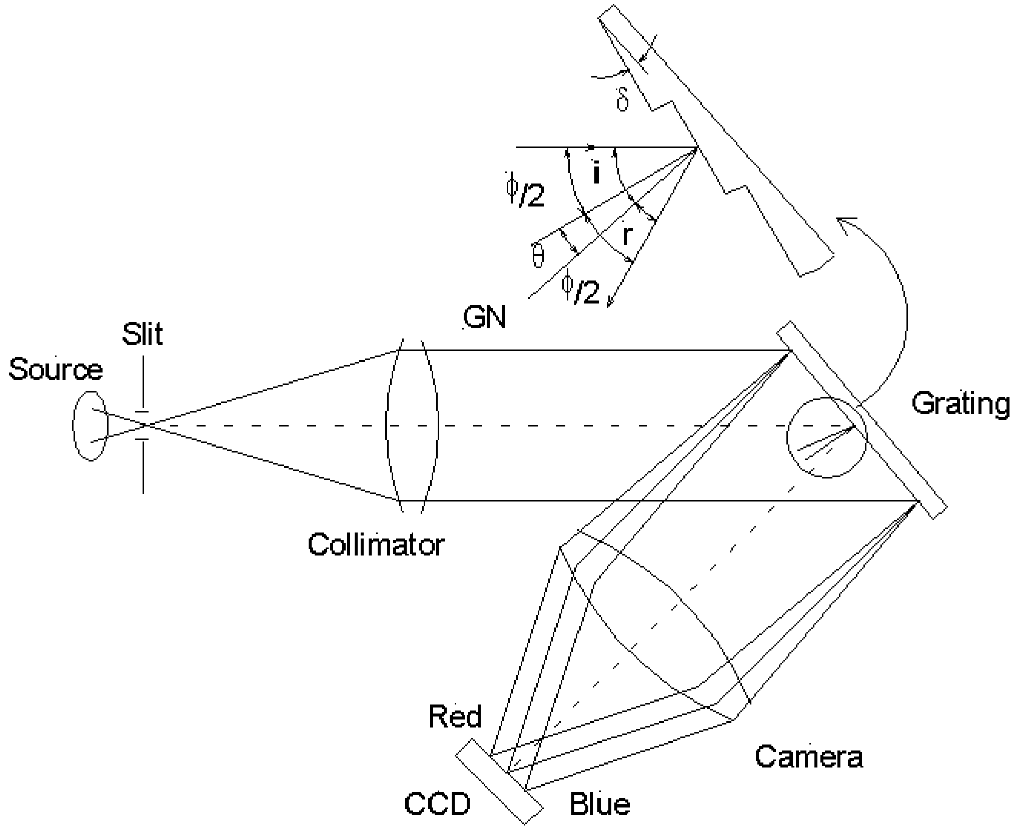
Spectrographs 1.1

- A simple spectrograph design:



Spectrographs 1.2

- Another simple design:



Focal lengths:

Slit-to-collimator

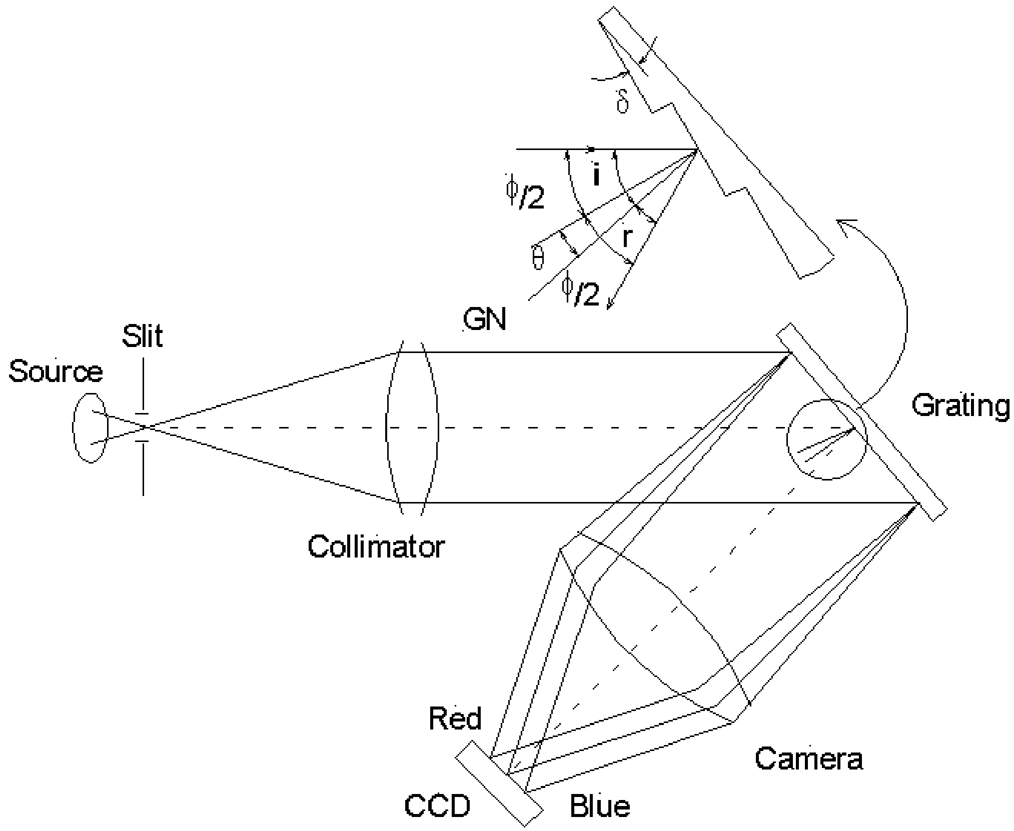
$$f_{coll}$$

Camera-to-CCD

$$f_{cam}$$

Spectrographs 1.2

- Another simple design:



Important angles:

Collimator-to-camera: (fixed)

Incident (collimator-to-grating normal GN):

$$i \equiv \alpha$$

Reflected (relative to GN):

$$r$$

Blaze angle

$$\delta \equiv \theta$$

Diffracted envelope:

$$\beta$$

Spectrographs 1.3

- Diffracted envelope *I*(β)

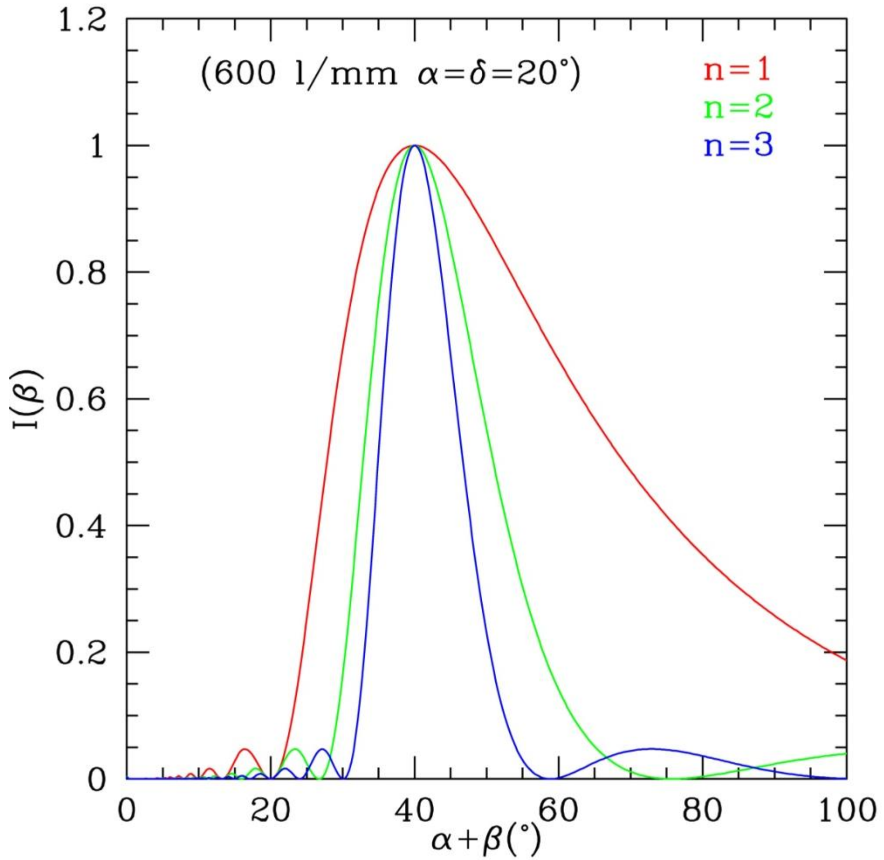
(Gray, The Observation and Analysis of Stellar Photospheres, 1976, 1992, 2005, 2008)

- Constructive interference occurs at

$$\frac{n\lambda}{d} = \sin(\alpha) + \sin(\beta)$$

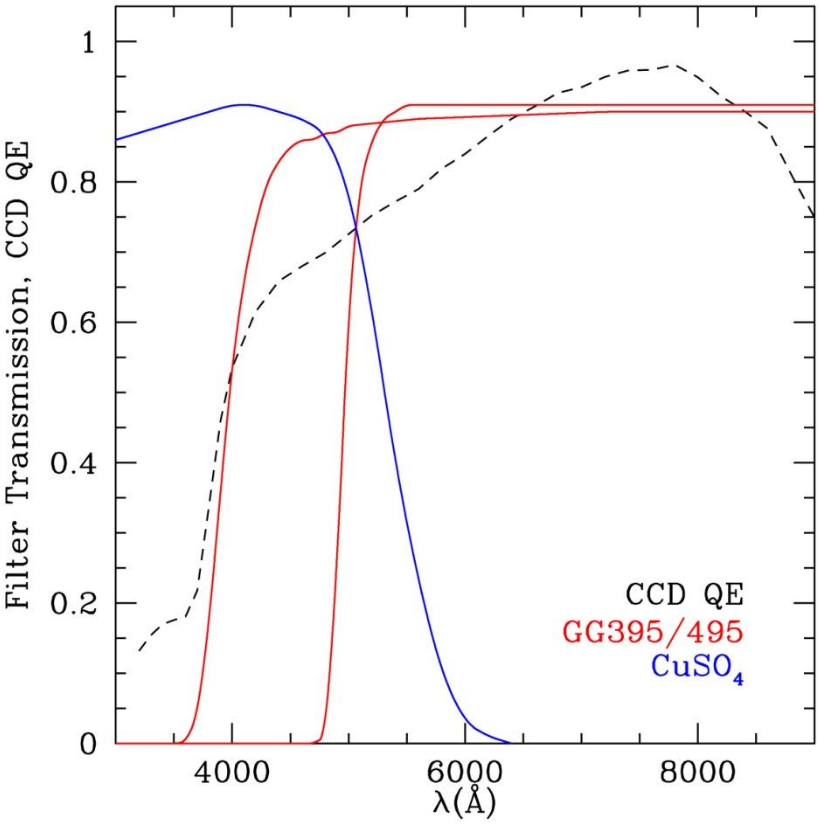
(grating equation!)

- Problem of order overlap solved with order-sorting filters.



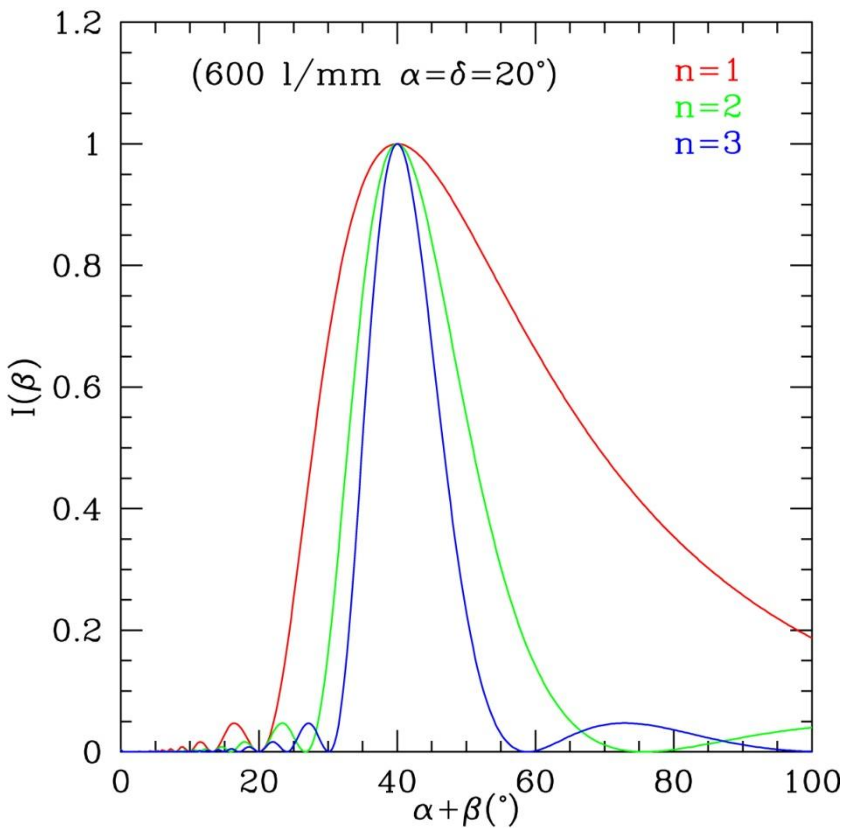
Spectrographs 1.4

- Examples of order sorting filters:
  - GG395 long-pass
    $\lambda>3950$
  - GG495 long-pass
    $\lambda>4950$
  - CuSO4 short-pass
    $\lambda<6000$
- Note: the CCD QE also limits the wavelength range



Spectrographs 1.5

- A source of white-light produce the diffracted envelope I(β), but
- Insert long-pass GG495 before the slit,
- And recompute I(β) taking into account CCD QE (MIT/LL on FORS2).
- Note: other effects include shadowing (angle limits), ghosts ...



Spectrographs 1.5

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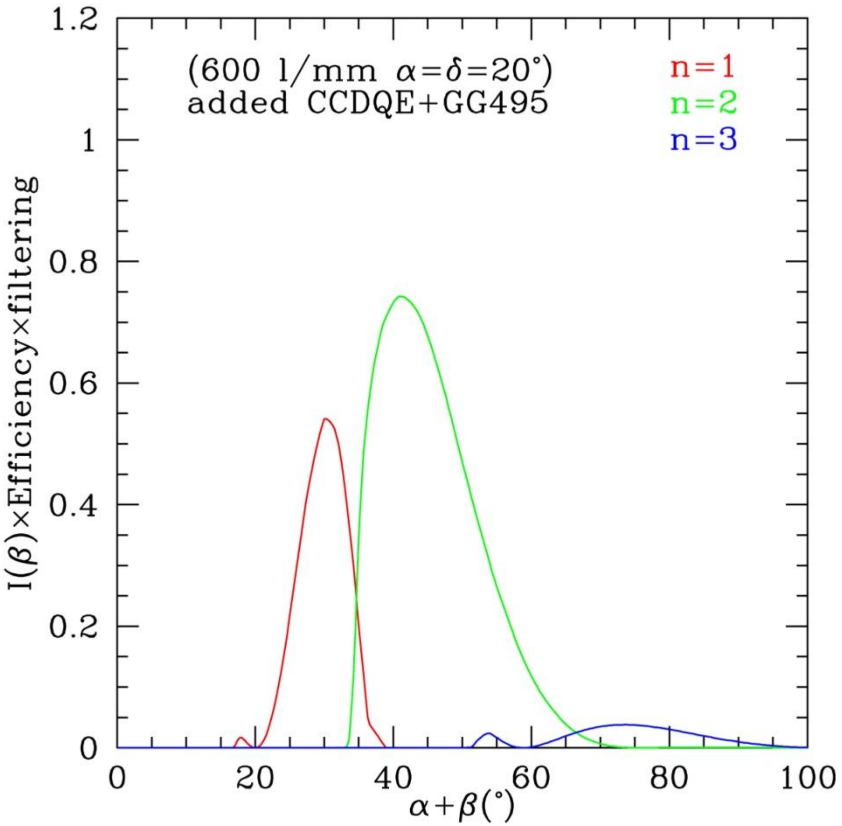


Spectrographs 1.6

Atmospheric transmittance T(λ)

(Patat et al. 2011):

1) O_3: bands 5000-7000Å and <3400Å

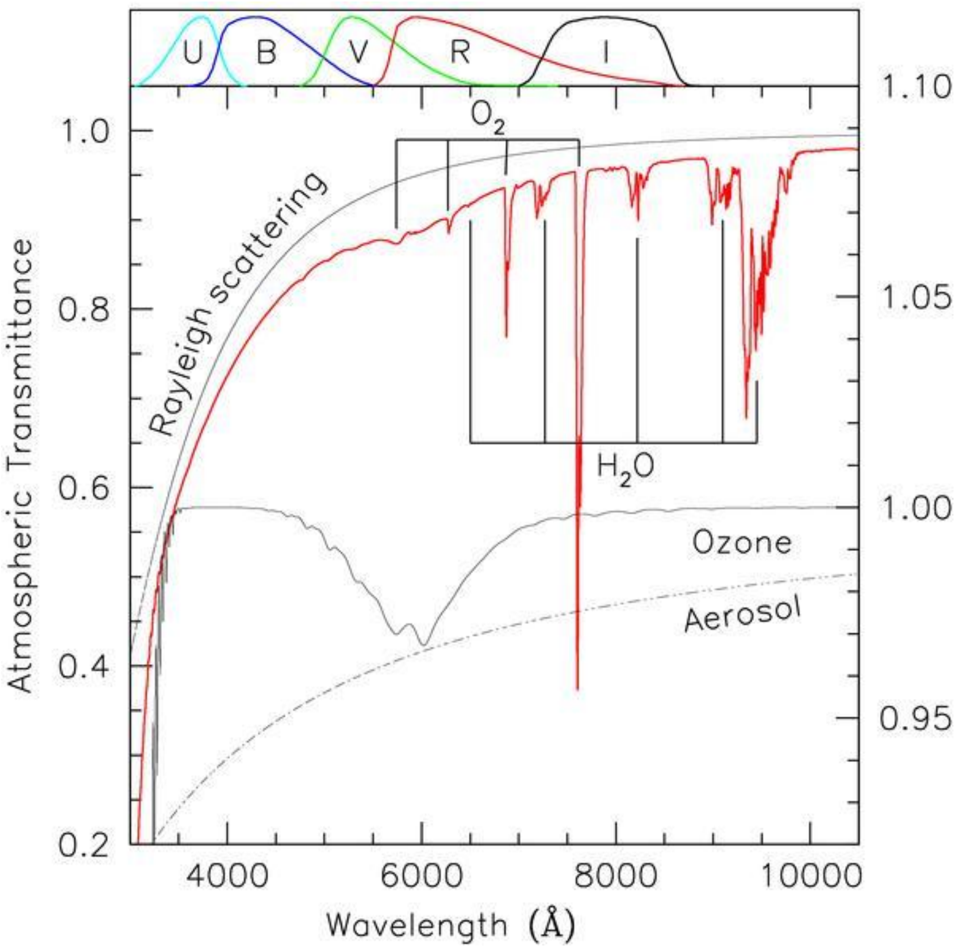
2) Rayleigh: O_2

3) Aerosol: volcanic dust

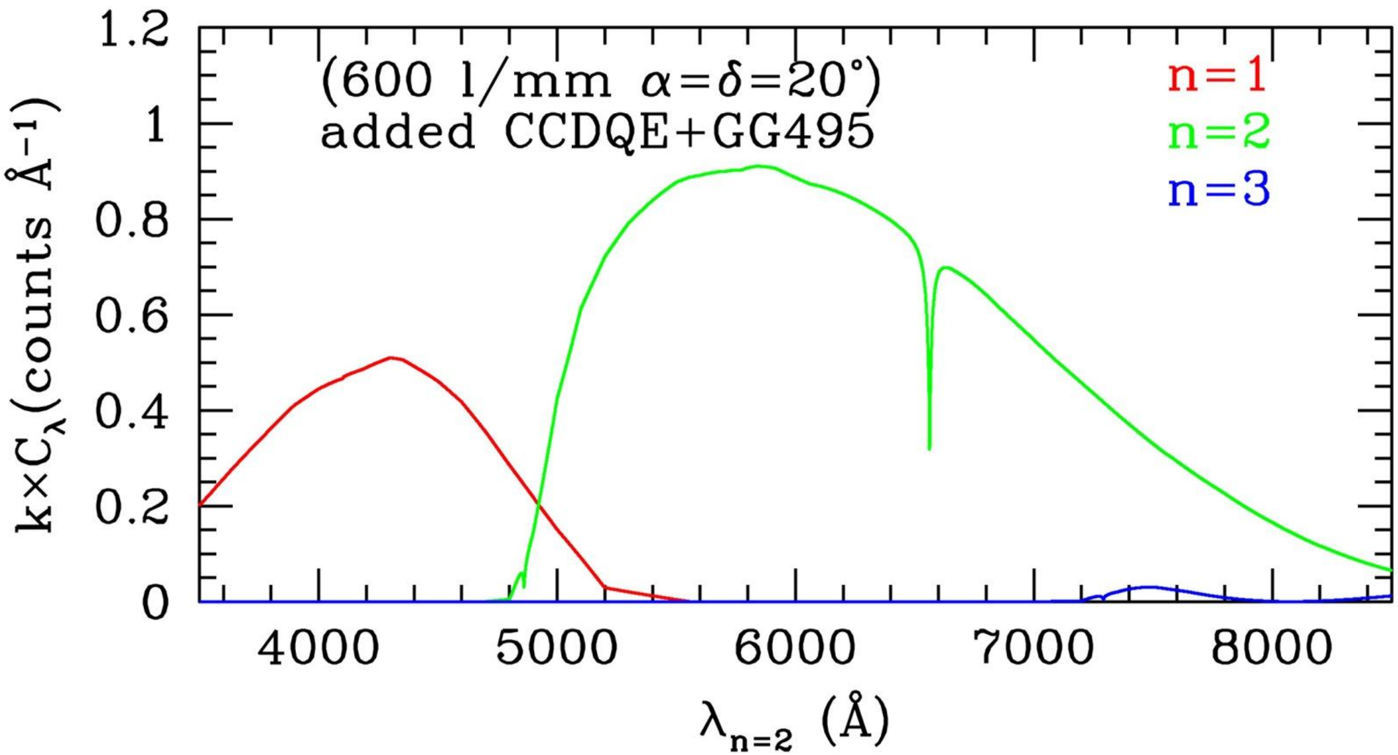
4) H_2O: bands > 6500Å

5) O_2: bands > 6500Å

UV spectra and U band affected most.



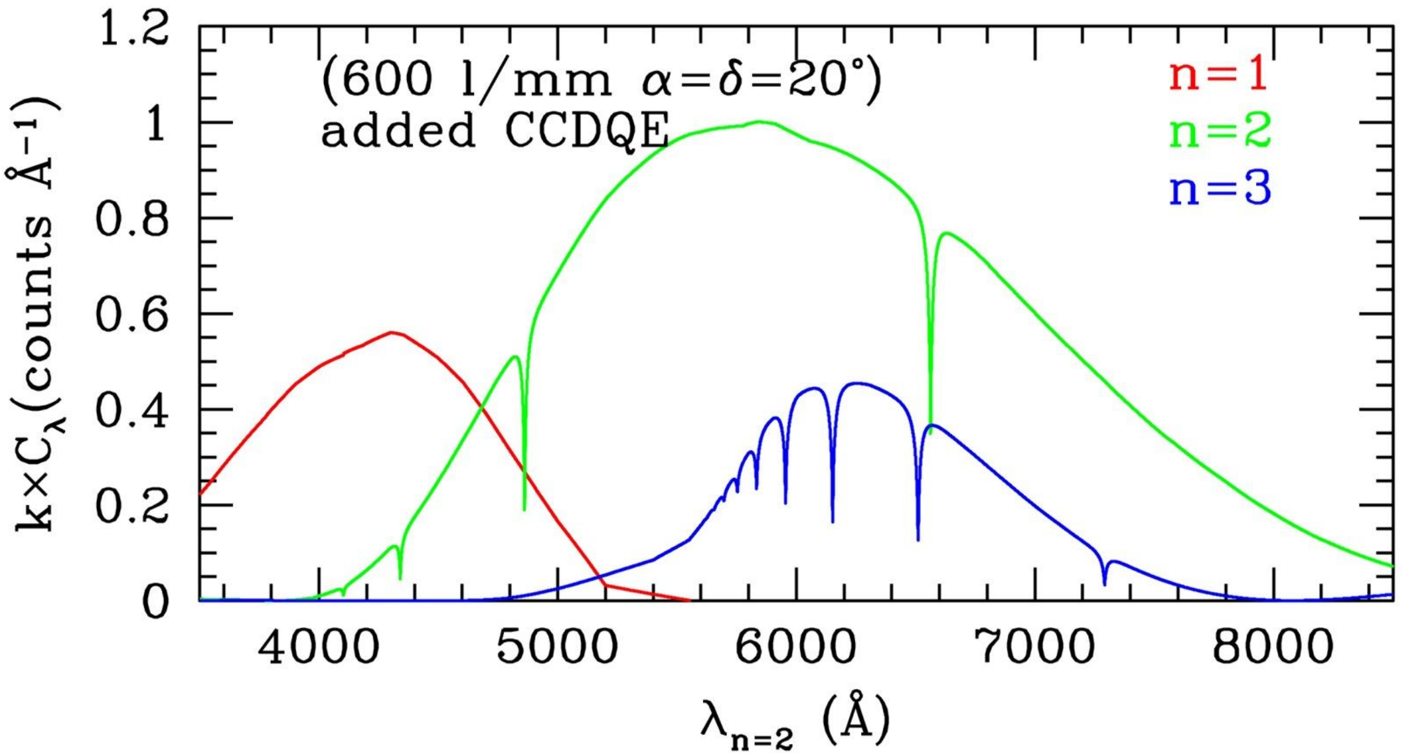
Spectrographs 1.7



We now summarize our work by applying this set up to a stellar spectrum:

$$C(\lambda) = kI(\beta \to \lambda)F(\lambda)QE(\lambda)Fil(\lambda)T(\lambda)$$

Spectrographs 1.7



We now summarize our work by applying this set up to a stellar spectrum:

$$C(\lambda) = kI(\beta \rightarrow \lambda)F(\lambda)QE(\lambda)\cancel{Fil}(\lambda)T(\lambda)$$

Spectrographs 1.8

- Resolving power

Definition: $$R = \frac{\lambda}{\Delta\lambda},$$

where $\Delta\lambda$ is the FWHM of the instrumental (dispersion) profile $IP(\lambda-\lambda')$.

Describe $R(\lambda-\lambda')$ with a normalized Gaussian function (or measure it):

$$IP(\lambda-\lambda') = \frac{1}{\sigma\sqrt{\pi}}\exp[-((\lambda-\lambda')/\sigma)^2]$$

Spectrographs 1.9

- Dispersion profile

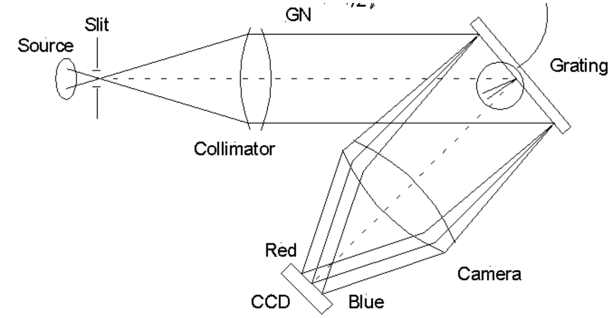
$$IP(\lambda-\lambda')=\frac{1}{\sigma\sqrt{\pi}}\exp[-((\lambda-\lambda')/\sigma)^2]$$

Where σ is the half-width at 1/e related to the FWHM (or resolution $\Delta\lambda$) by FWHM≈1.666σ –*demonstrate*-.

Best practice is to measure the dispersion profile with narrow emission lines (e.g., sky lines). A Gaussian is a good approximation.

Note: the Gaussian is also written in terms of the variance *s*, where $\sigma=\sqrt{2}\ s$.

Spectrographs 1.10



- Spectrograph resolving power:

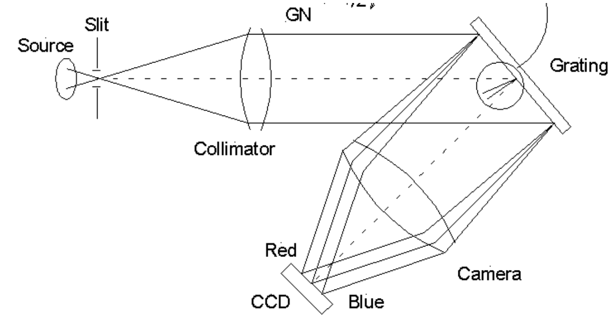
The image size at the telescope focus (i.e. at the slit) limits the spectral resolution.

The theoretical limit is the grating resolution:

$$\Delta\lambda = \frac{\lambda}{W}\frac{d}{n} \Rightarrow R = \frac{\lambda}{\Delta\lambda} = \frac{nW}{d}$$

Where W is the grating size (width), d the ruling spacing, n the order... (see Gray 1976, 1992, 2005, 2008)

Spectrographs 1.11



- Spectrograph resolving power:

The theoretical limit is the grating resolution :

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

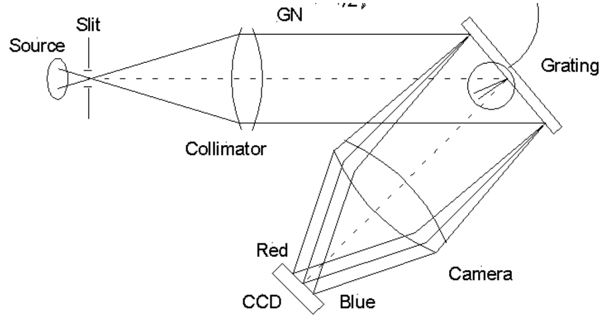
- Example: grating KPC10A on the RC-spec at KPNO 4m...

W≈ 100 mm, *d*=1/316 mm, and *n*=1:

$$R \approx 30{,}000$$

Which would be nice! High-dispersion spectrograph nearly reach this limit thanks to large focal lengths.

Spectrographs 1.12



- Spectrograph resolving power:

The effective spectrograph resolution is set by the image angular dimension which introduces small angular deviation in the light path all the way to the CCD!

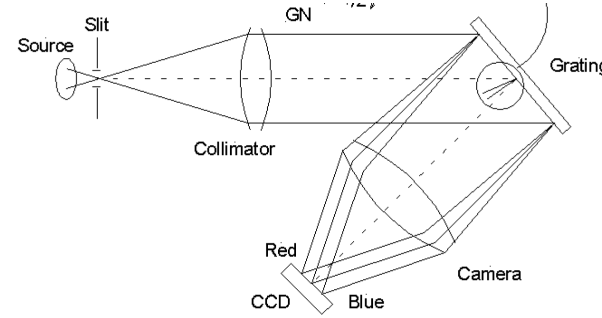
- Follow the light through the spectrograph:

(1) From the slit to the collimator

$$d\alpha = \frac{W'}{f_{coll}}$$

W' is the slit width, f_{coll} is the collimator focal length (sketch upper-right) $d\alpha$ is the angular size of the slit at the collimator, hence at grating...

Spectrographs 1.13



- Follow the light through the spectrograph:

(1) From the slit to the collimator ...

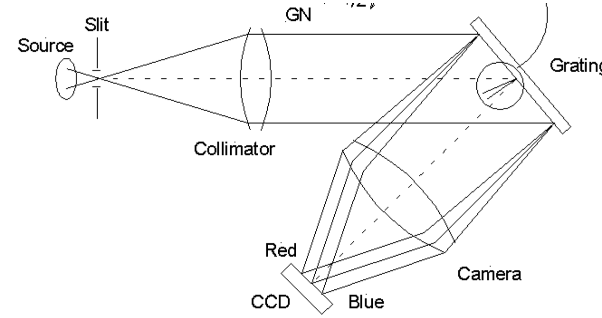
(2) Next follow the light diffracted at angle β off the grating ... With the grating equation:

$$\frac{n\lambda}{d} = \sin\alpha + \sin\beta \Rightarrow (\cos\alpha)d\alpha + (\cos\beta)d\beta = 0$$

$$d\beta = -\frac{\cos\alpha}{\cos\beta}d\alpha = -\frac{\cos\alpha}{\cos\beta}\frac{W'}{f_{coll}}$$

Where we applied the result for $d\alpha$ from (1) and $d\beta$ is the image size leaving the grating...

Spectrographs 1.14



- Follow the light through the spectrograph:

(1) From the slit to the collimator ... $d\alpha$

(2) Off the grating ... $d\beta$

(3) Now onto the camera and the CCD (x coordinates).

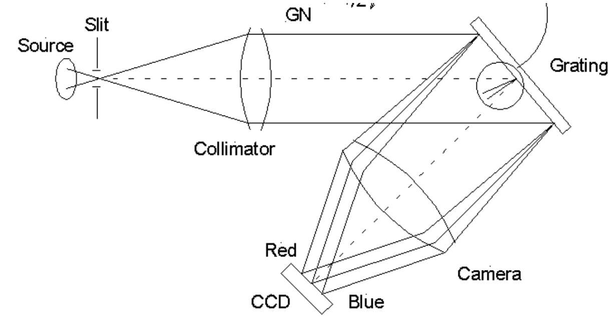
$$dx = f_{cam} d\beta \Rightarrow \frac{d\beta}{dx} = \frac{1}{f_{cam}}$$

Which introduces a ``blur'' $d\lambda$ along the wavelength axis... Next:

$$\frac{d\lambda}{dx} = \frac{d\lambda}{d\beta}\frac{d\beta}{dx} = \frac{1}{f_{cam}}\frac{d\lambda}{d\beta}$$

Which is our new expression for the dispersion ...

Spectrographs 1.15



- Follow the light through the spectrograph:

(1) From the slit to the collimator ... $d\alpha$

(2) Off the grating ... $d\beta$

(3) On the CCD ... dx and $d\lambda$

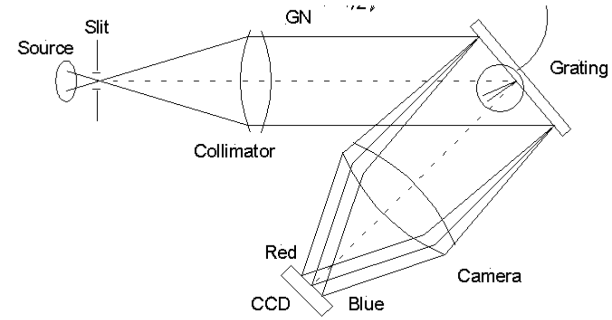
(4) Using again the grating equation find $d\lambda/d\beta$

$$\frac{n\lambda}{d} = \sin\alpha + \sin\beta \Rightarrow \frac{d\lambda}{d\beta} = \frac{d}{n}\cos\beta$$

And the dispersion relation now reads:

$$\frac{d\lambda}{dx} = \frac{d}{nf_{cam}}\cos\beta$$

Spectrographs 1.16



- Further refinement of the dispersion relation:

$$\frac{d\lambda}{dx} = \frac{d}{nf_{cam}} \cos\beta$$

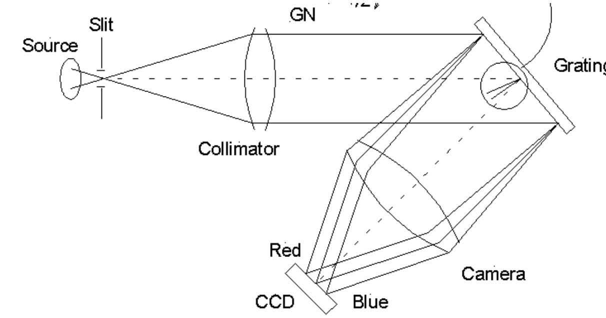
(1) Define *w* as the projected slit width on the CCD, where f_{cam}/f_{coll} is called the slit (de)magnification:

$$w \equiv dx = f_{cam} d\beta = f_{cam}\left(-\frac{\cos\alpha}{\cos\beta}\frac{W'}{f_{coll}}\right) = -\frac{\cos\alpha}{\cos\beta}\frac{f_{cam}}{f_{coll}}W'$$

(2) Define the resolution:

$$\Delta\lambda \equiv \frac{d\lambda}{dx} w \Rightarrow \Delta\lambda = w\frac{d}{n\,f_{cam}}\cos\beta = -\frac{d}{n}\frac{\cos\alpha}{f_{coll}}W'$$

Spectrographs 1.17



- Apply our *dispersion relation* and *resolution* formulae to the KPNO4m RC-spec (f_{coll}=1161mm f_{cam}=265 mm) and KPC10A (d=1/316 mm) grating in first order.

(1) Dispersion:

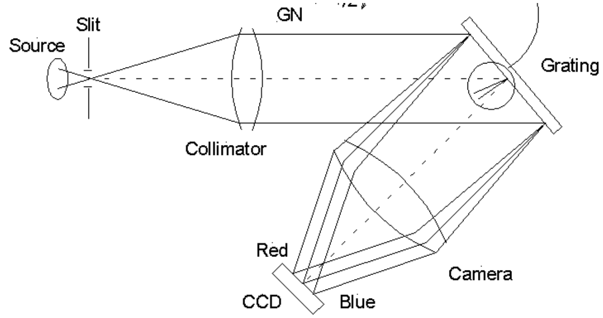
$$\frac{d\lambda}{dx} = \frac{d}{nf_{cam}} \cos\beta = 1.19 \times 10^{-5} = 119\,\dot{A}\text{mm}^{-1}$$

or 2.87 **Å**/pix for 24μm per pixel. Total coverage ≈4000**Å**.

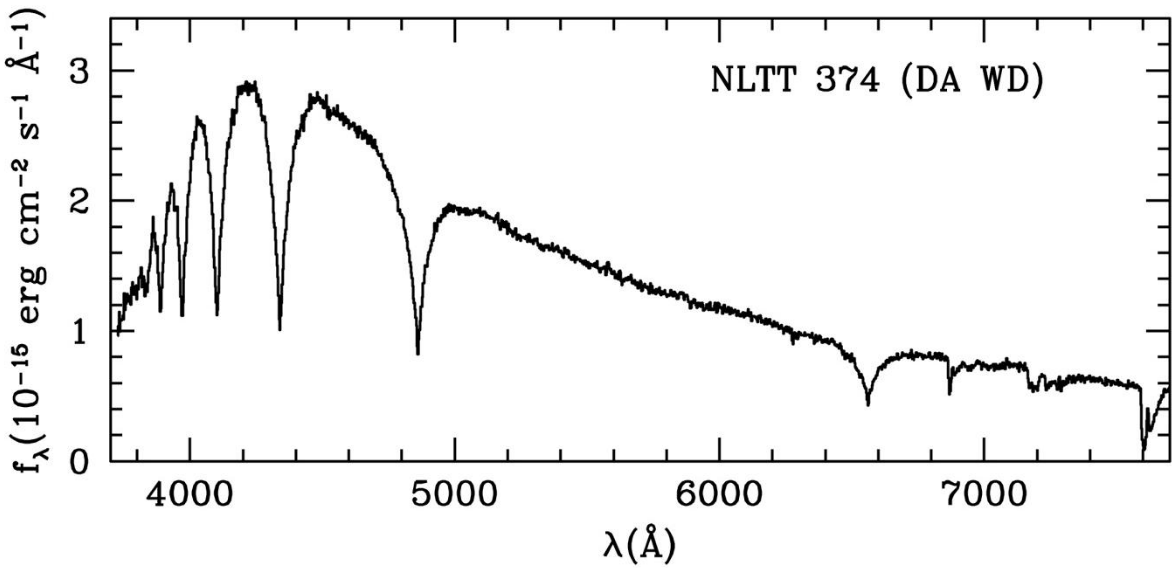
(2) Resolution for W′=300μm (or 2″):

$$\Delta\lambda \equiv -\frac{d}{n}\frac{\cos\alpha}{f_{coll}} W' \approx 8.2\dot{A}$$

Spectrographs 1.18

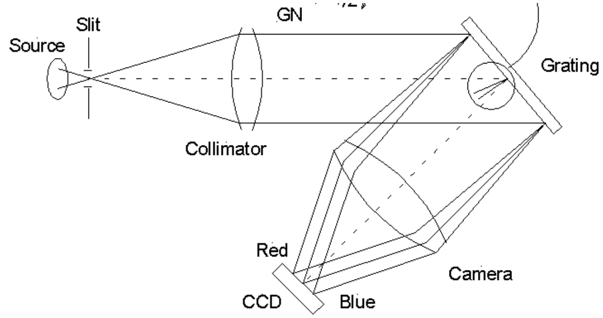


- Example of KPNO4m/RC-spec data:



NLTT 374 (V=16) observed May 27, 2014 (1800 s).
KPC10A in first order, $\Delta\lambda$=5.7**Å** (slit=225 μm or 1.5″).

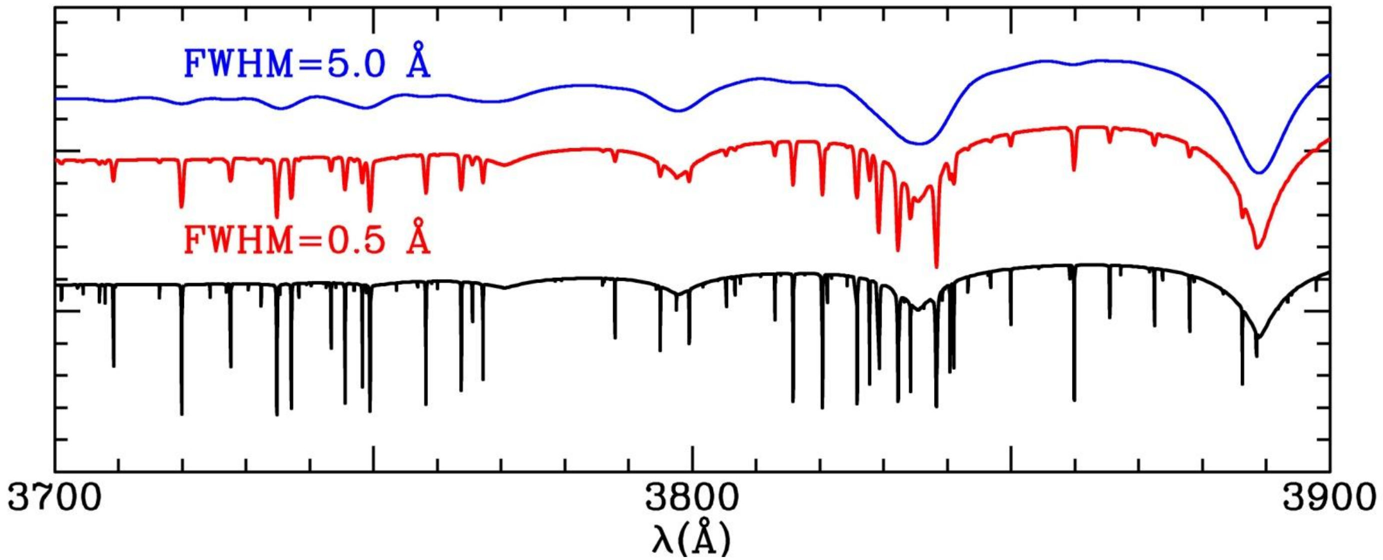
Spectrographs 1.19



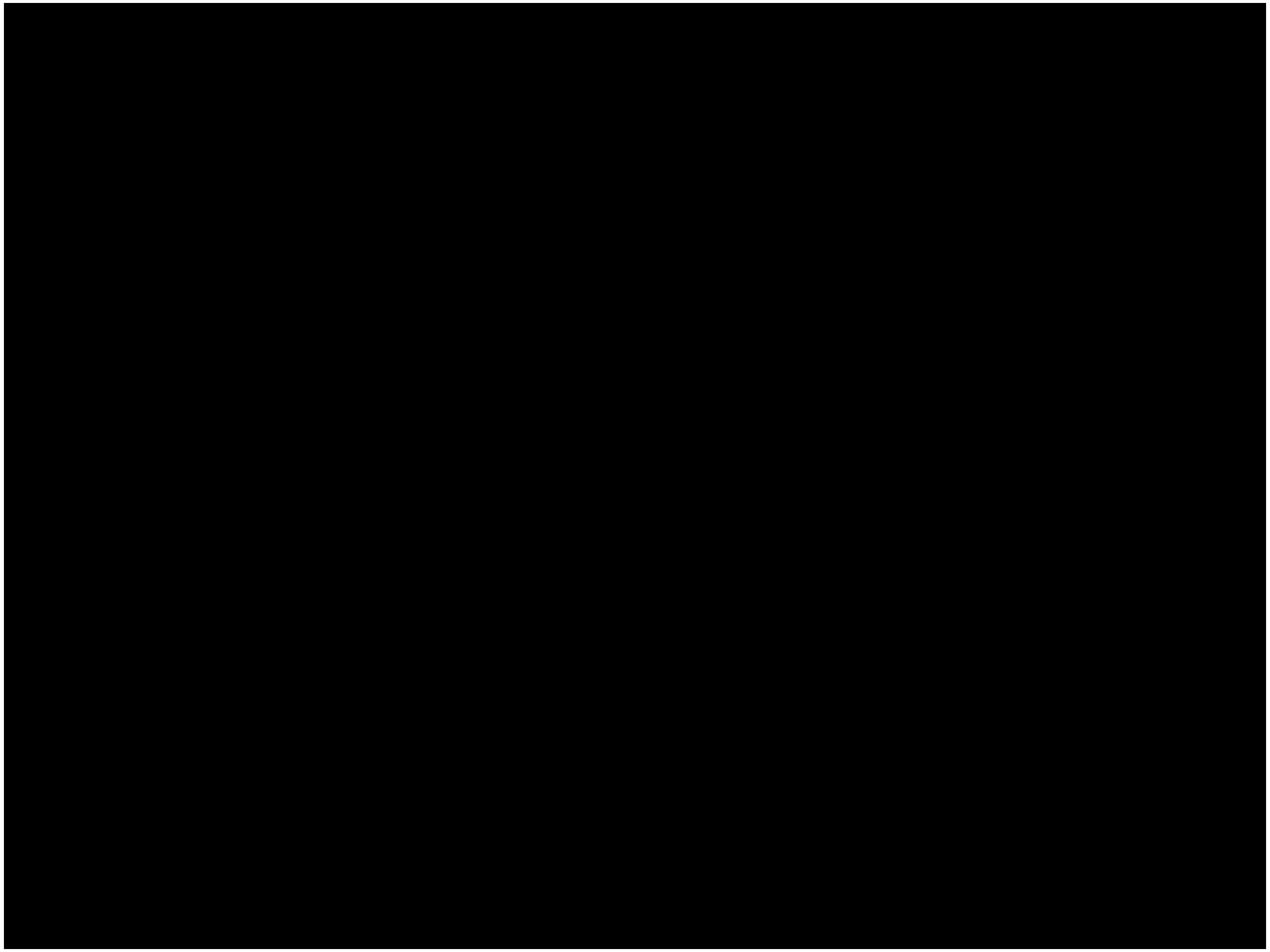
- Two movies illustrating:

i. The effect of instrument resolution FWHM=0.5 **Å** On a Balmer/FeI spectrum. For example with ESO VLT/Xshooter. Convolution done with a Gaussian (slides 1.9-1.10).

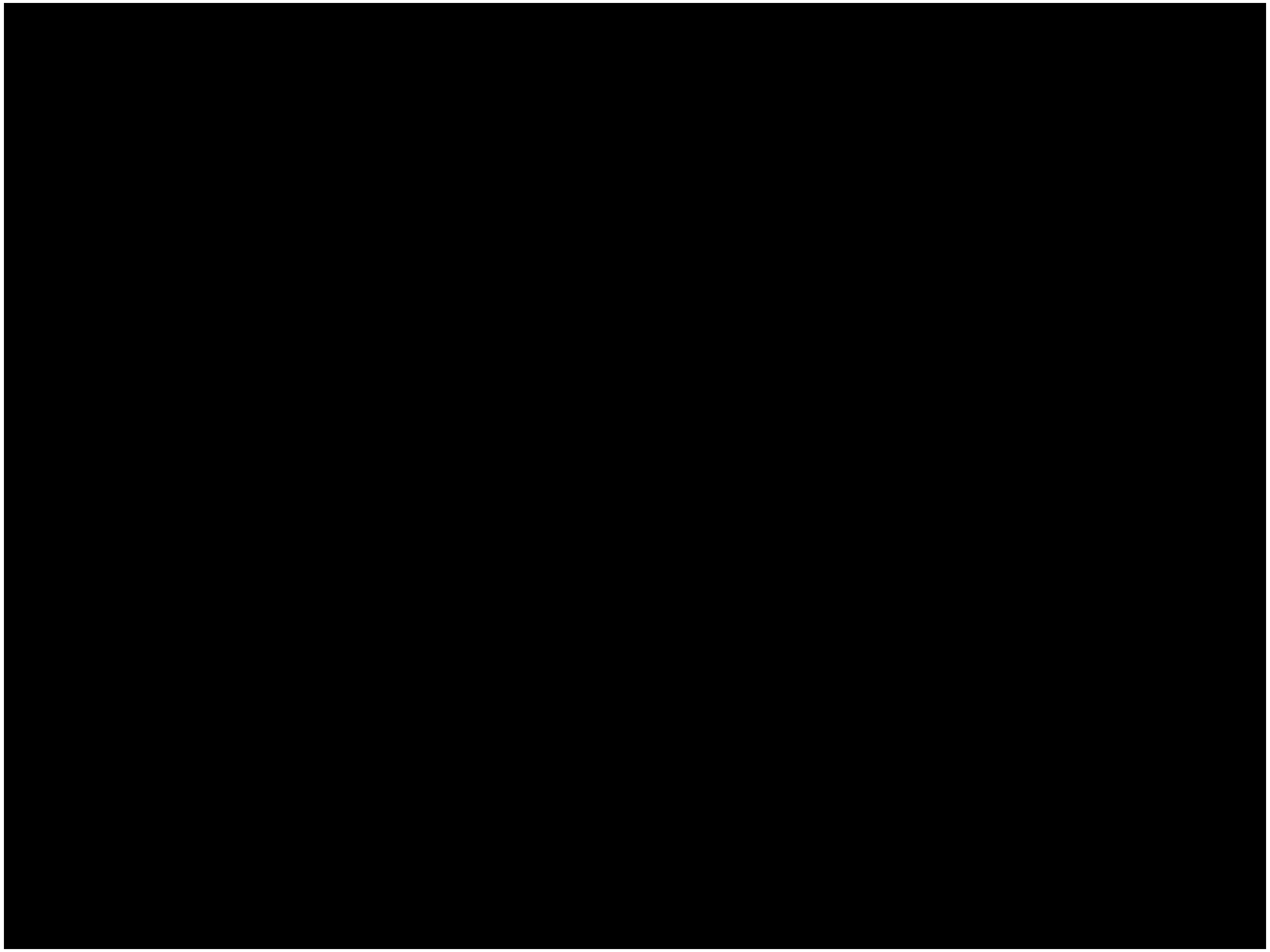
ii. Same as i. but with FWHM=5 **Å**. For example with NTT/EFOSC or KPNO4m/RC-spec.



Spectrographs 1.20 FWHM=0.5Å



Spectrographs 1.21 FWHM=5.0Å

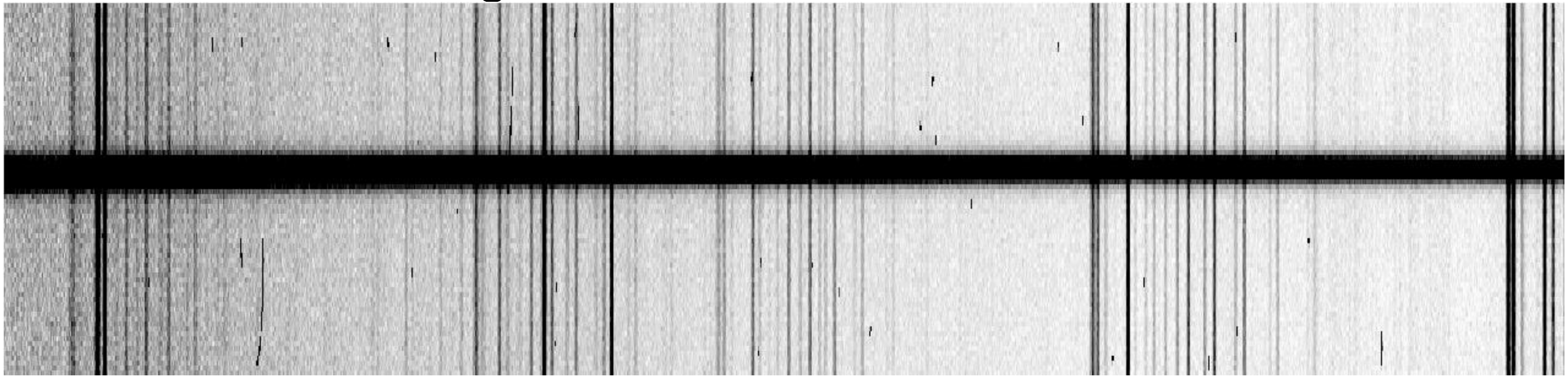


Data processing 1.1

- Calibration Plan (Simplified): Before you start ...
  1. Set the grating at the desired tilt angle specifying the spectral order and central λ, and chose order-sorting filter accordingly. Take note of the observation format: CCD size and readout binning.
  2. Obtain comparison arc (HeNeAr) throughout the night, and biases (readout-signature...take many!) and flats (many, well-exposed) at the beginning.
  3. Hopefully you obtained some science exposures.
  4. We'll work with FORS2 long-slit, the Xshooter intermediate dispersion echelle, and the SSO/2.3m Wide Field Spectrograph (WiFeS) integral field.
  5. Set the slit of the FORS and X-shooter spectrographs to the parallactic angle to counteract atmospheric refraction! WiFeS' integral field is designed to avoid such loss.

Data processing 1.2

- A FORS2 Calibration Plan (Simplified): CCD Science image ...

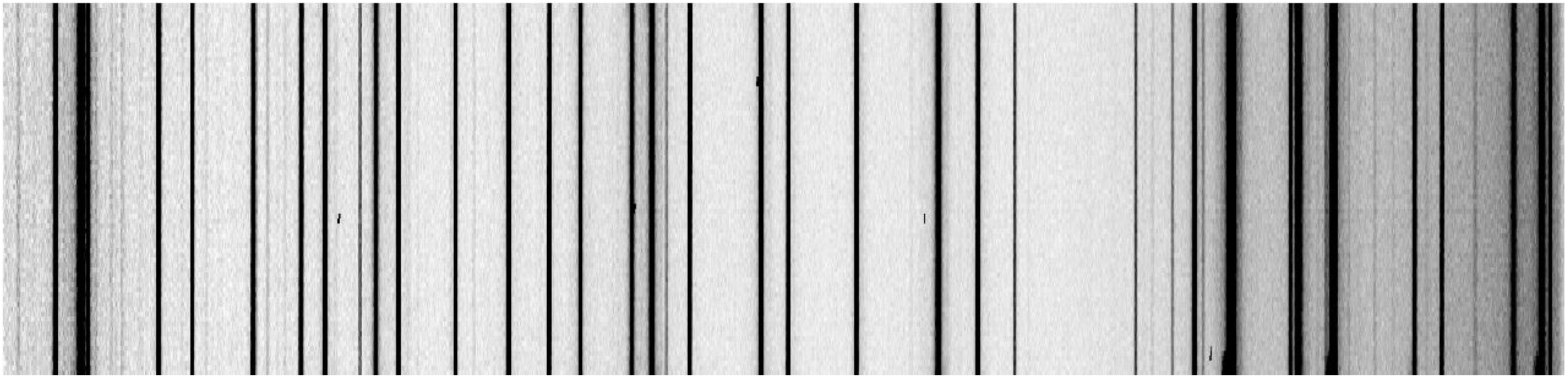


The trimmed image shows 75×2040 pixels (sky 0.25″/pix vs λ 0.73**Å**/pix), binned 2×2.

It shows sky lines and the spectral trace (aperture) for the white dwarf NLTT13015 (ESO; PI Kawka).

Data processing 1.3

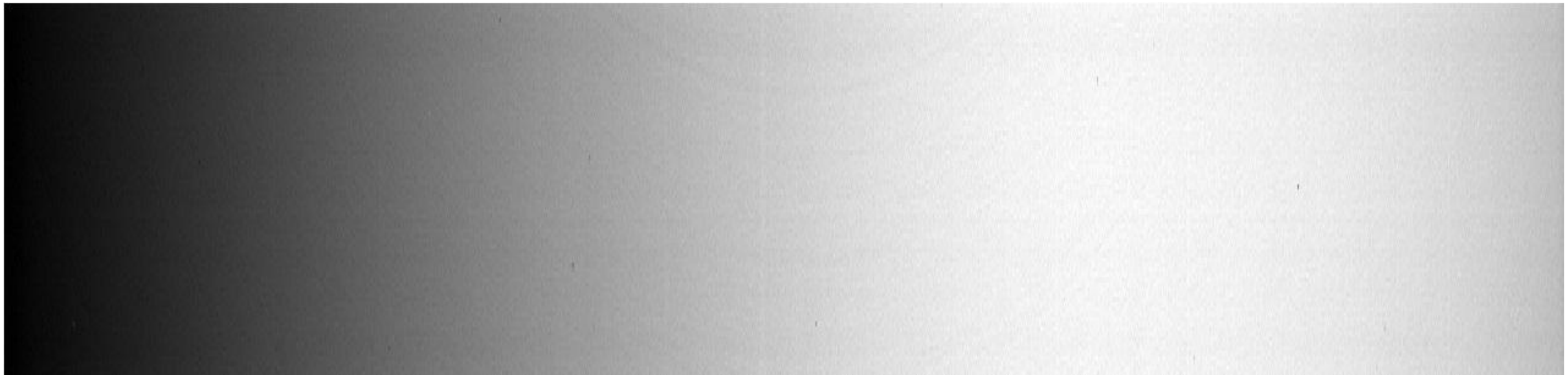
- A FORS2 Calibration Plan (Simplified): HeNeAr image ...



The comparison arc exposure uses the same format as the science images (75×2040 pixels binned 2×2). Used to measure $d\lambda/dx$ (dispersion).

Data processing 1.4

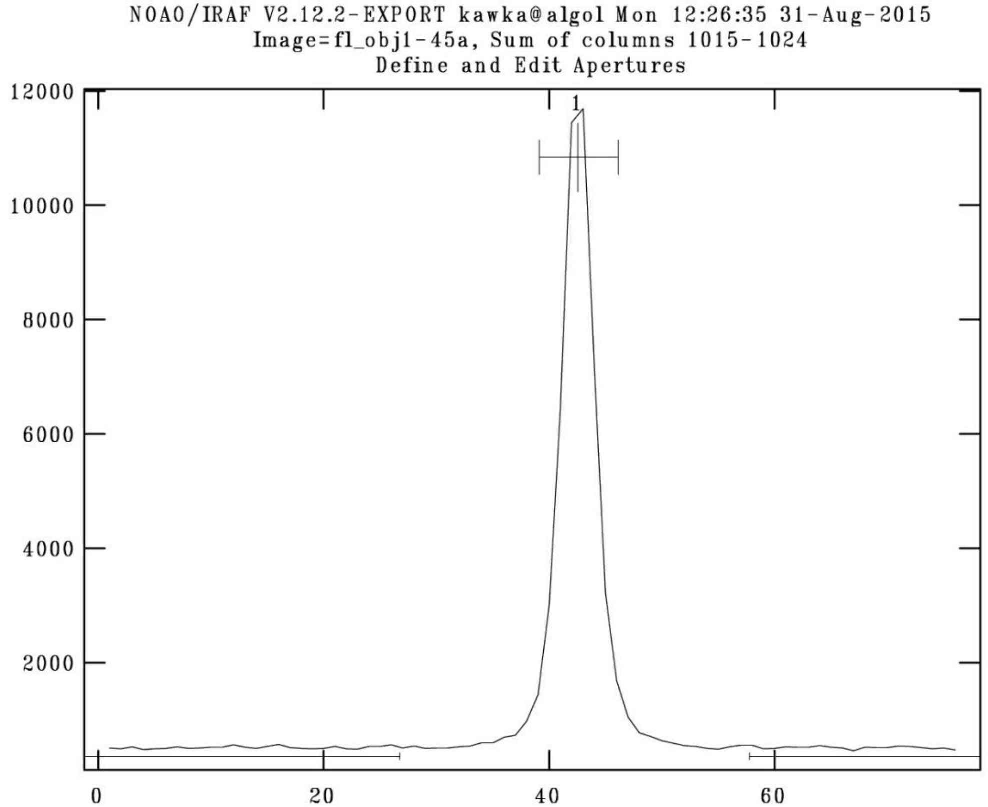
- A FORS2 Calibration Plan (Simplified): Quartz-flat image ...



The quartz exposure uses the same format as the science images (75×2040 pixels binned 2×2). Used to remove small-scale instrument artefacts.

Data processing 1.5

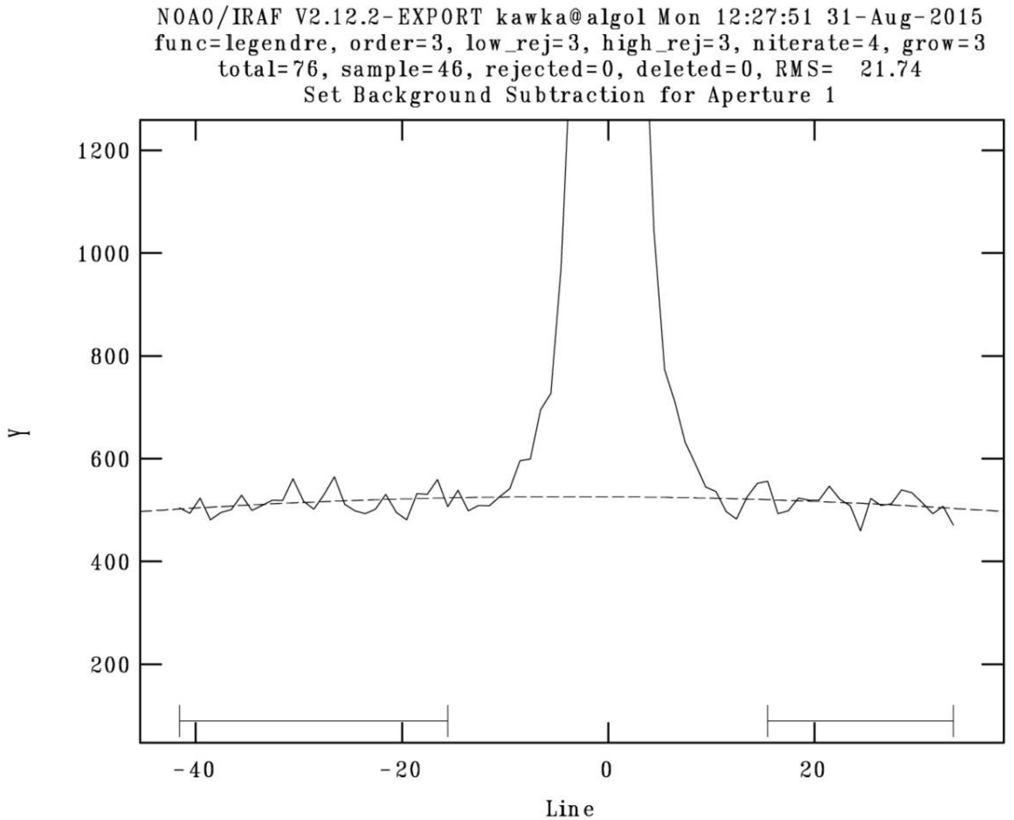
- A FORS2 Calibration Plan (Simplified):



The images are cleaned (bias-subtracted, flat-fielded). Use an IRAF (APALL) routine to extract aperture.

Data processing 1.6

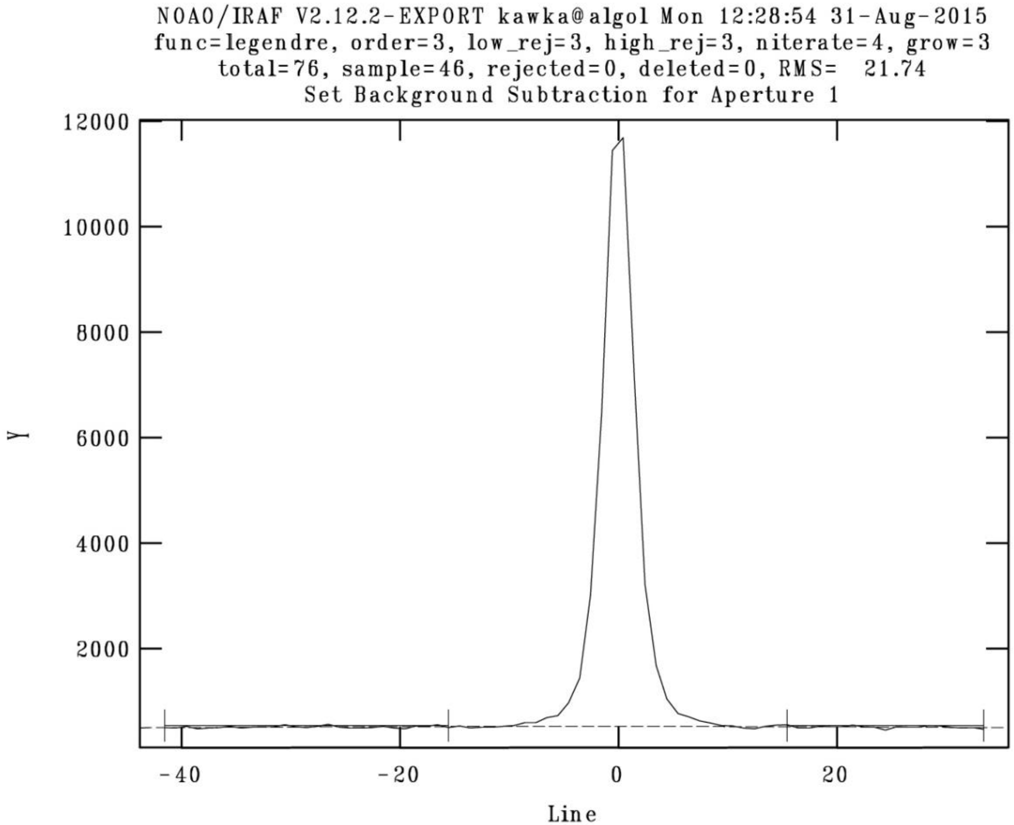
- A FORS2 Calibration Plan (Simplified):



Set the background and subtract with low-order function…

Data processing 1.7

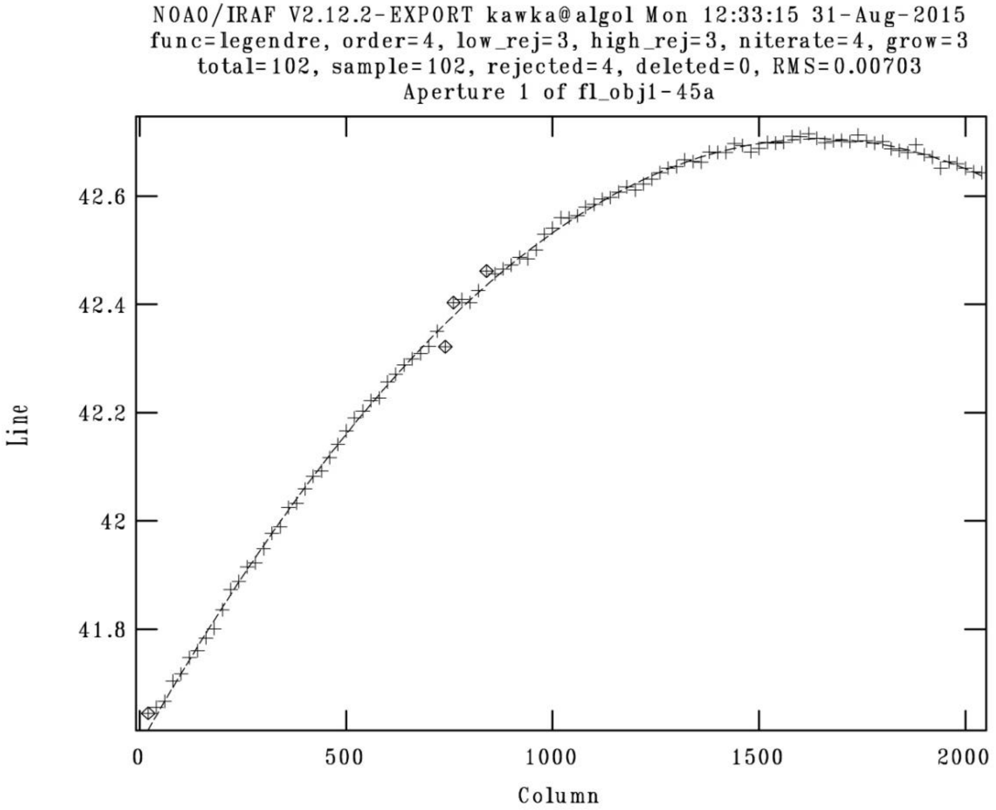
- A FORS2 Calibration Plan (Simplified):



Set the background and subtract with low-order function…

Data processing 1.8

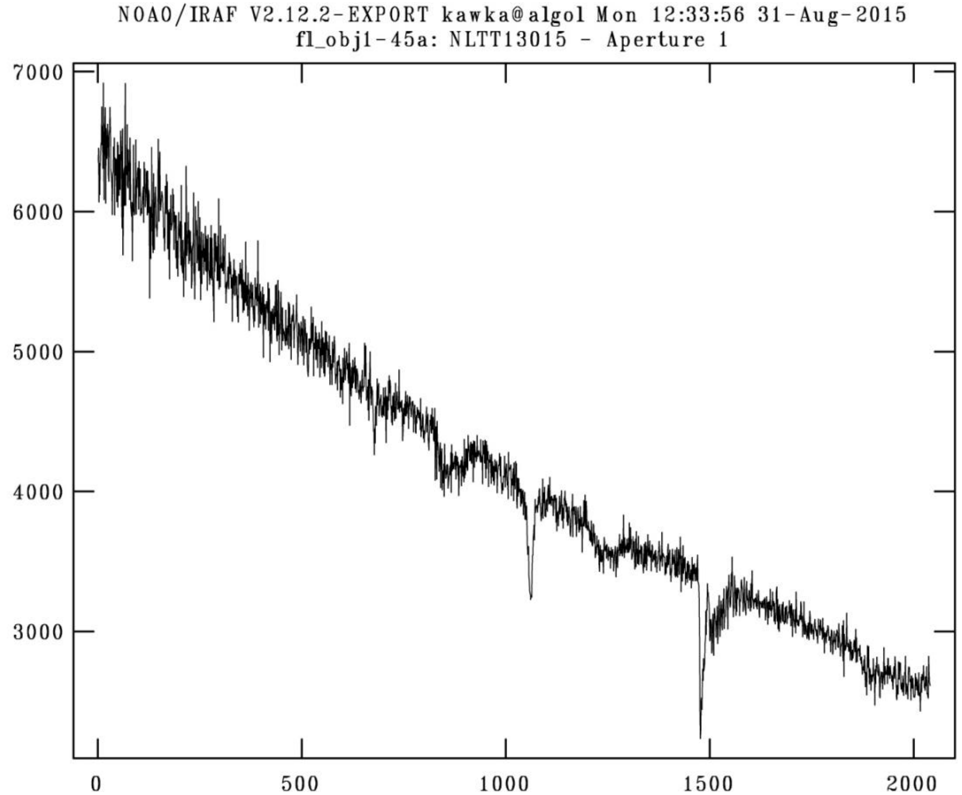
- A FORS2 Calibration Plan (Simplified):



Fit the aperture with a low-order function and trace x-y positions (column-line) on the image.

Data processing 1.9

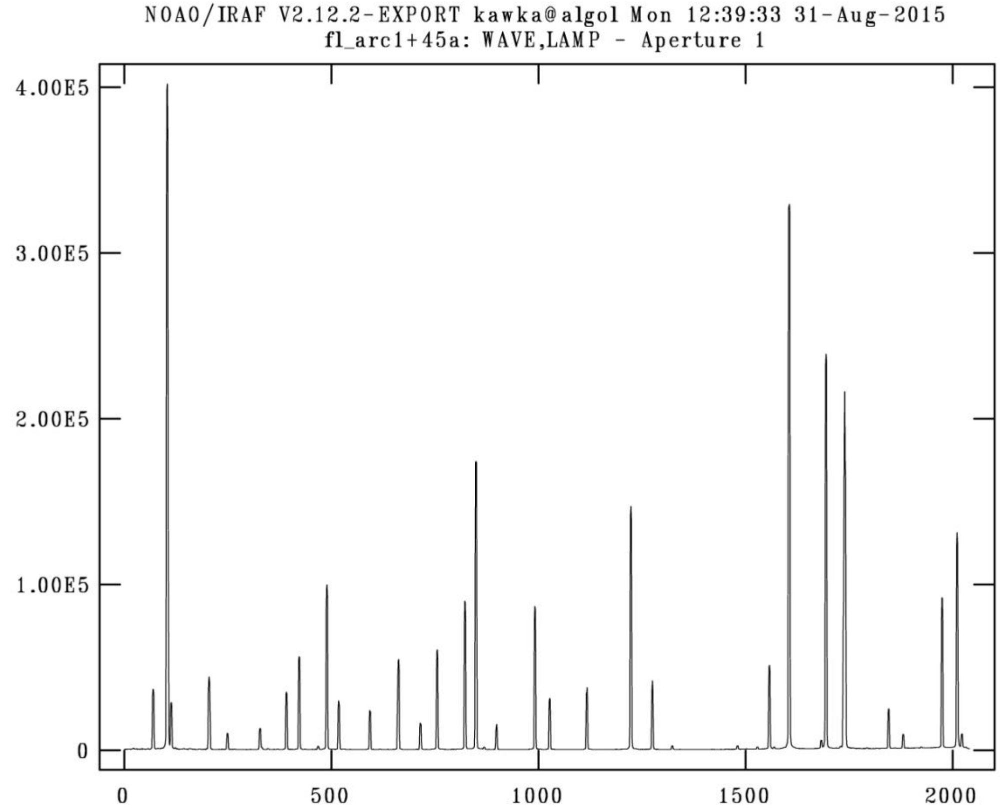
- A FORS2 Calibration Plan (Simplified):



The extracted spectrum remains in counts versus pixel coordinates. Spectral features are evident ...

Data processing 1.10

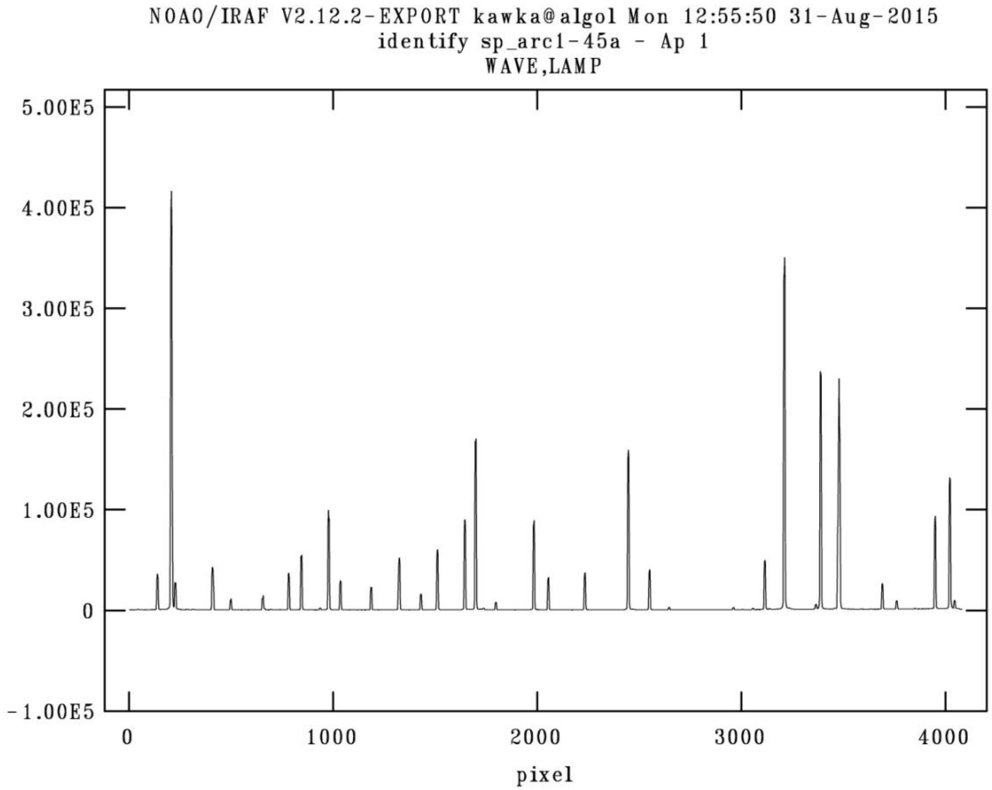
- A FORS2 Calibration Plan (Simplified):



The HeNeAr spectrum is extracted along the recorded position of the stellar spectrum.

Data processing 1.11

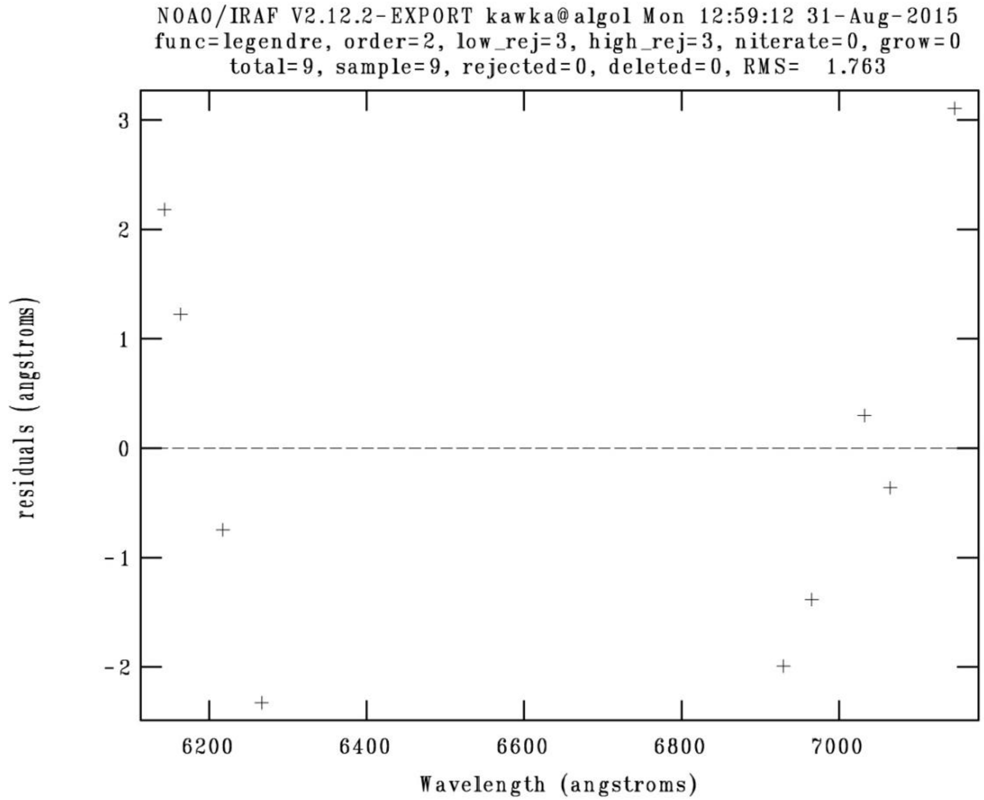
- A FORS2 Calibration Plan (Simplified):



The procedure IDENTIFY will match the observed HeNeAr spectrum with the laboratory line list and workout the dλ/dx function.

Data processing 1.12

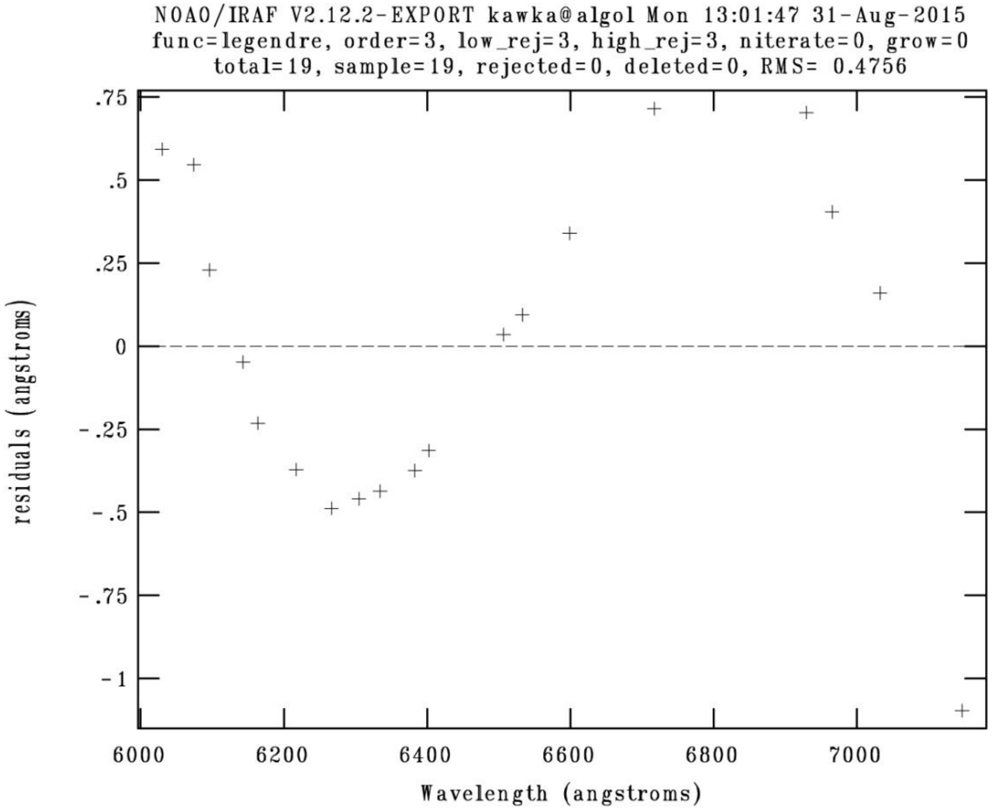
- A FORS2 Calibration Plan (Simplified):



Manually mark a few lines, fit low-order polynomials (Legendre) and start developing the dispersion function $d\lambda/dx$.

Data processing 1.13

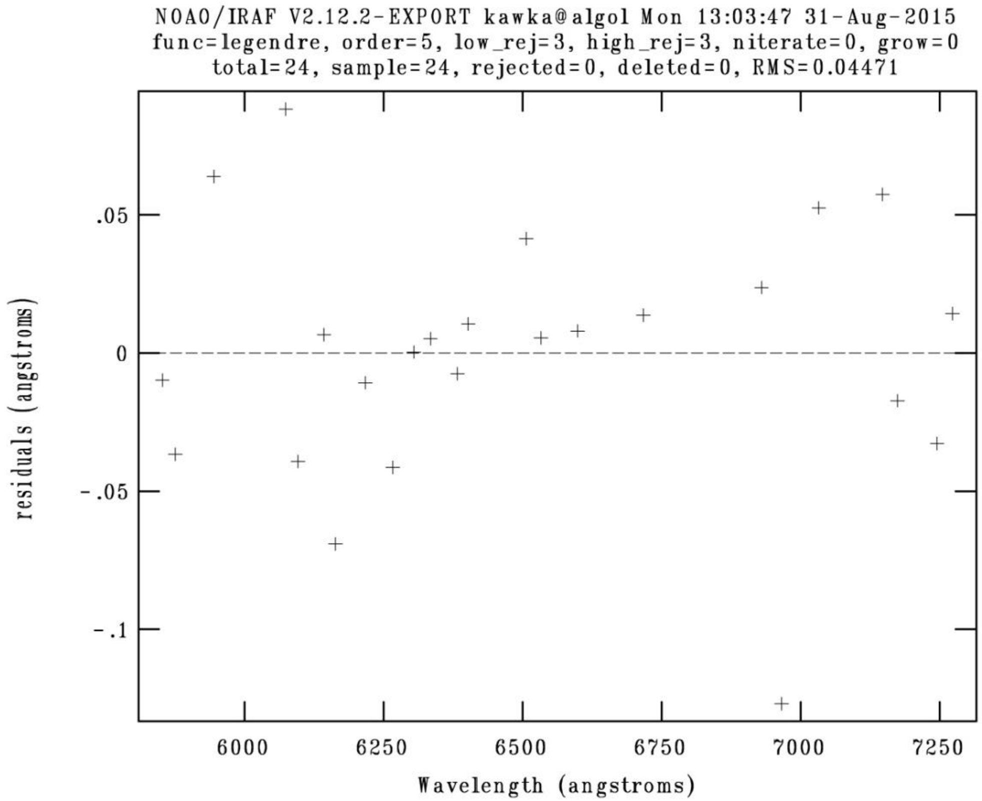
- A FORS2 Calibration Plan (Simplified):



Let IDENTIFY mark a few lines automatically and re-fit low-order polynomials (Legendre)...

Data processing 1.14

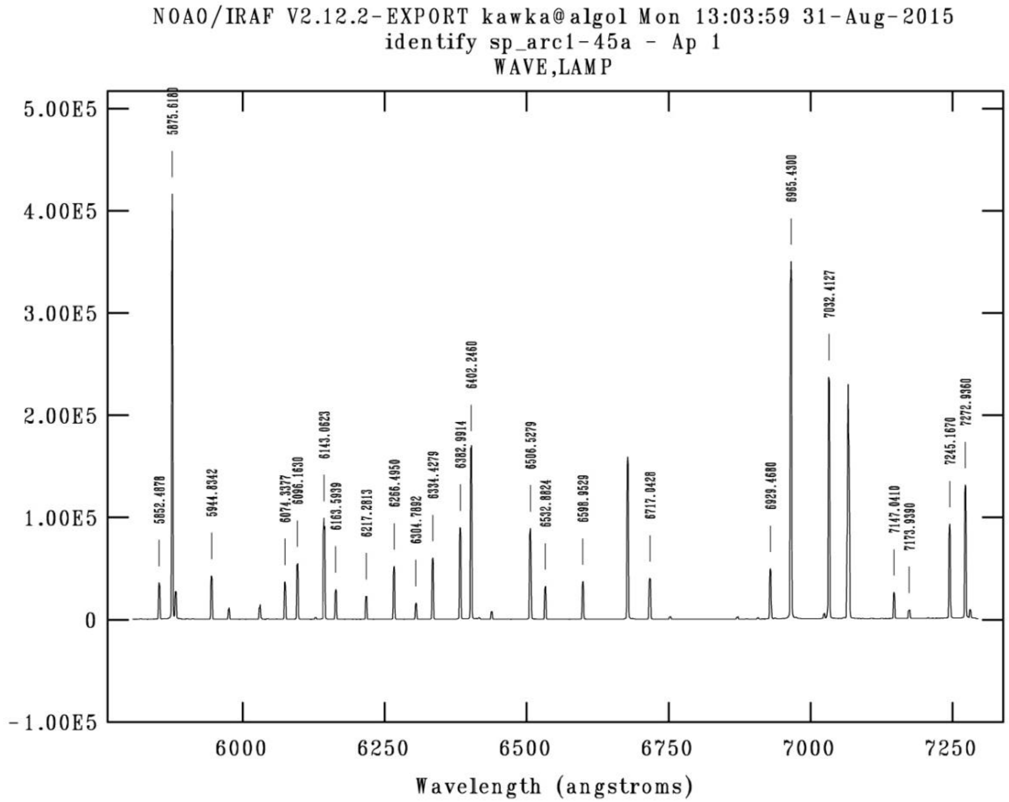
- A FORS2 Calibration Plan (Simplified):



Add a few lines, increase the order: residuals of only 0.04Å. The dispersion function is ready to be applied to raw the stellar spectrum

Data processing 1.15

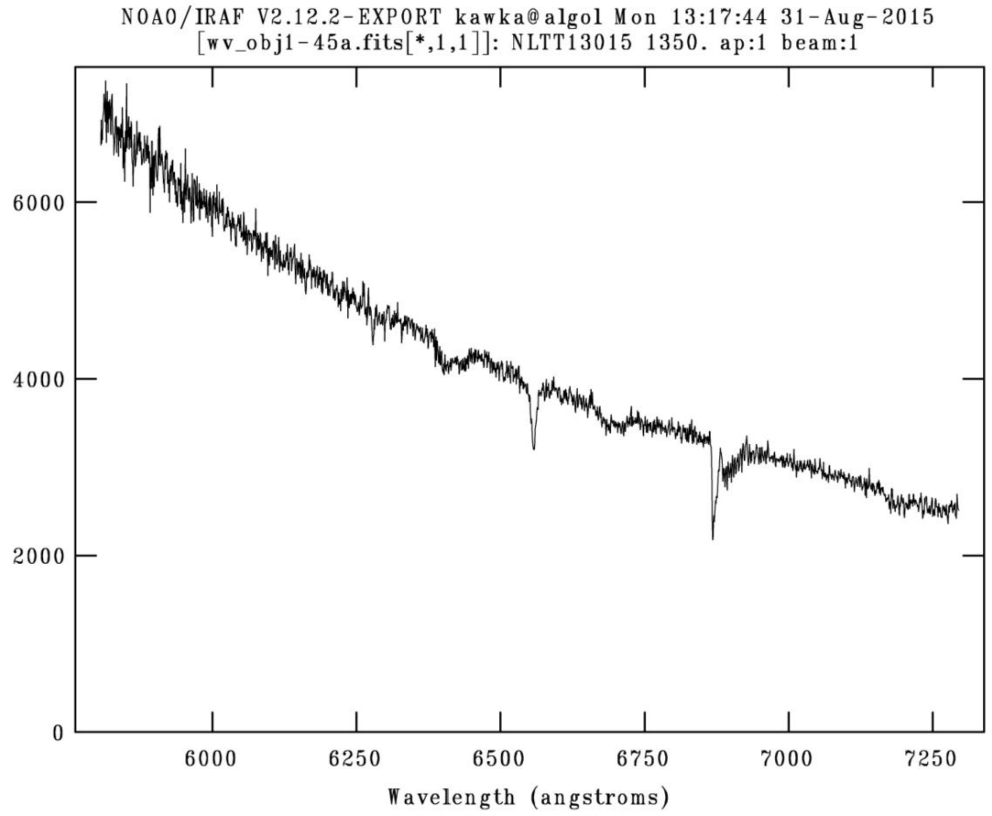
- A FORS2 Calibration Plan (Simplified):



This dispersion relation has an internal precision of 2 km/s. Systematic errors may well be 5 times larger.

Data processing 1.16

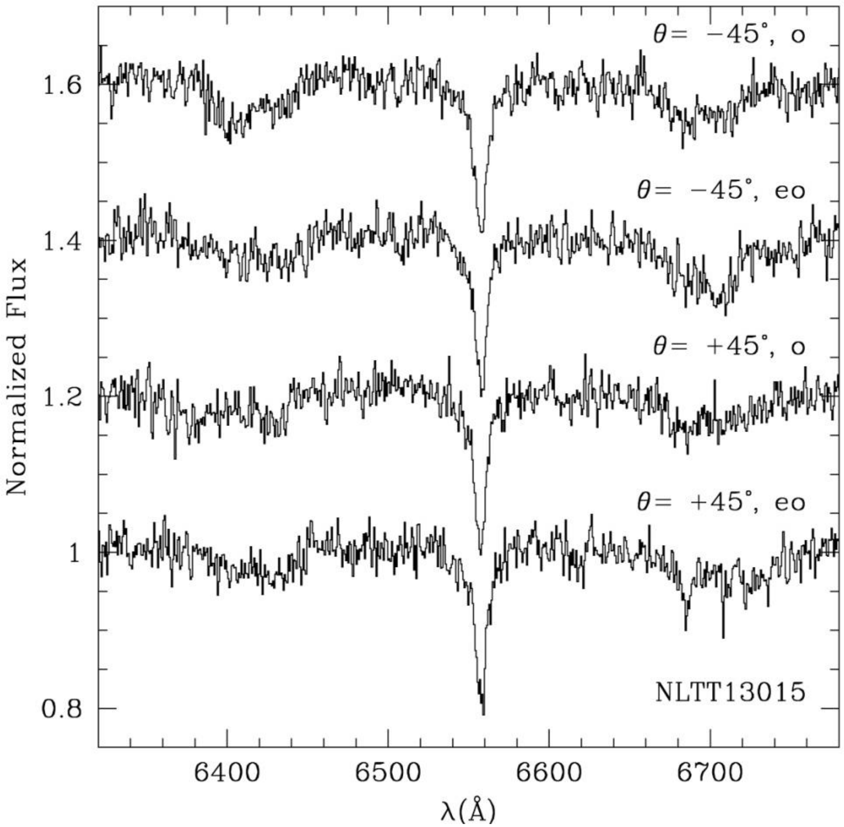
- A FORS2 Calibration Plan (Simplified):



This wavelength calibrated spectrum is now ready to be flux-calibrated against a flux calibration standard.

Data processing 1.17

- A FORS2 Calibration Plan (science results):



- The spectrum just reduced is part of a spectro-polarimetric set showing Zeeman-splitted Hα.
- Combined following:

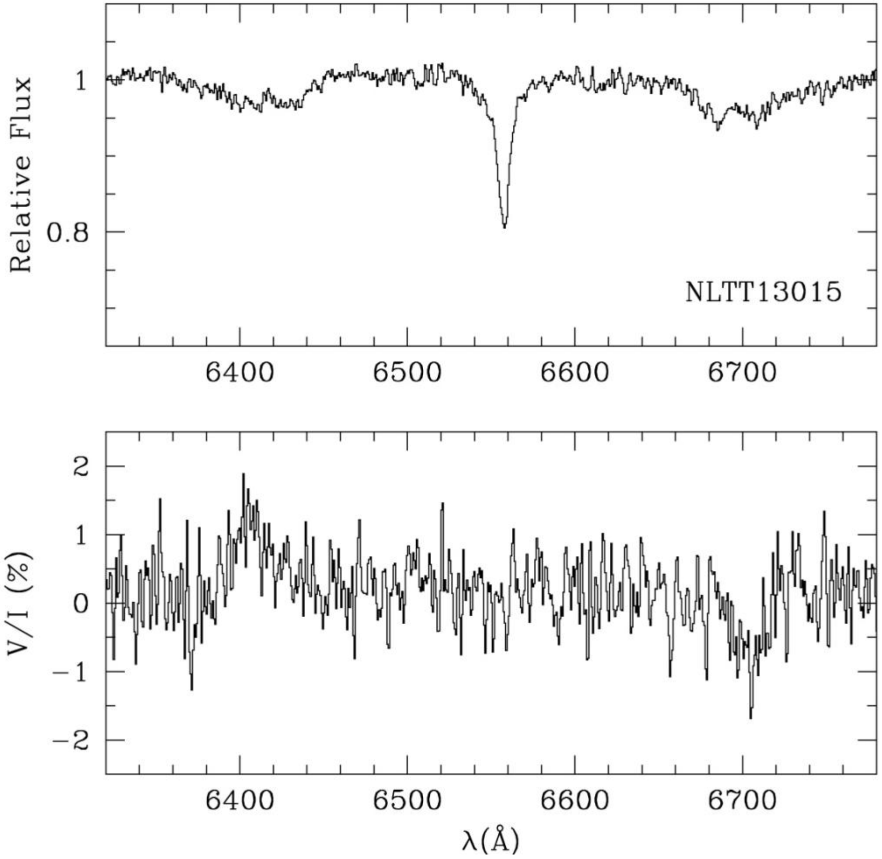
$$\frac{V}{I} = \frac{1}{2}\left[\left(\frac{f^{o} - f^{eo}}{f^{o} + f^{eo}}\right)_{\theta=+45} - \left(\frac{f^{o} - f^{eo}}{f^{o} + f^{eo}}\right)_{\theta=-45}\right]$$

The spectra deliver a polarization spectrum.

- Measurements obtained at two positions of retarder plate (±45°) help remove instrument/calibration biases.

Data processing 1.18

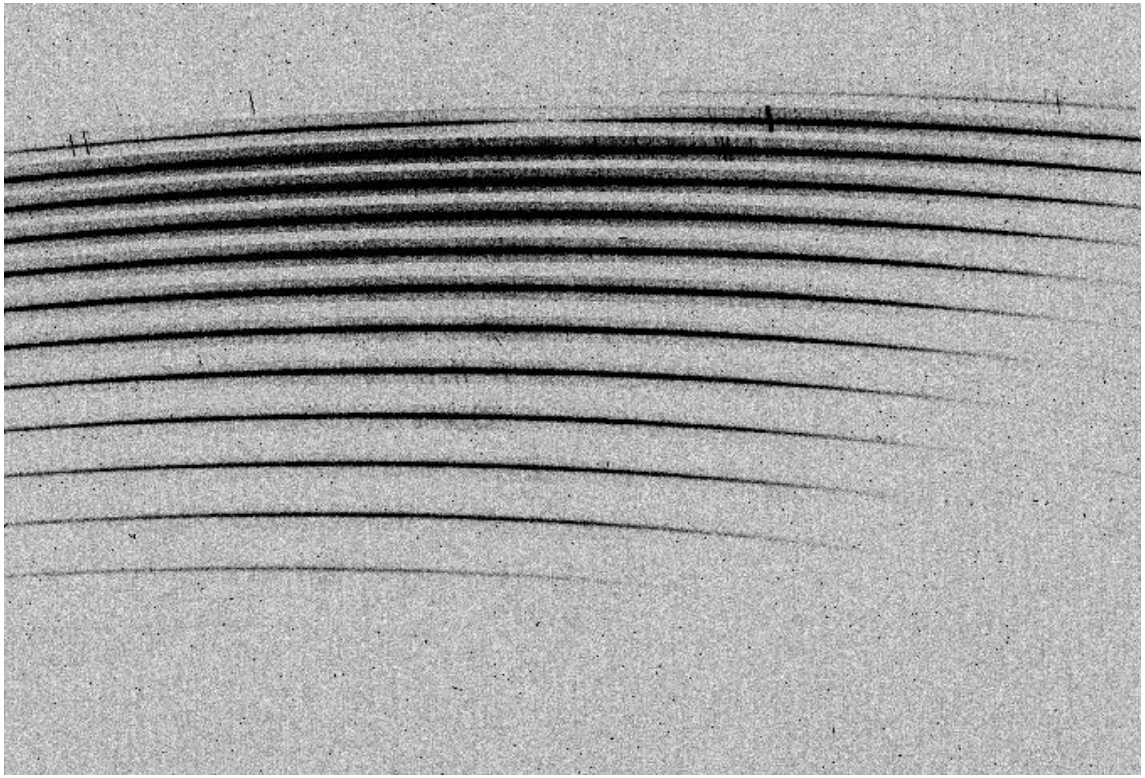
- A FORS2 Calibration Plan (science results):



- NLTT 13015 is a magnetic, hydrogen-rich white dwarf with T=5700 K and B=6-7.5 MG.
- There is no evidence of variability due to rotation of an offset dipole.
- However, structures in the σ± components show a complex field, certainly not dipolar.
- It is 3Gyr old (WD cooling life only) and kinematically peculiar (Kawka & Vennes 2012).
- V/I (B_l)and I (B_s)jointly constrain field geometry (inclination to viewer)

Data processing 1.19

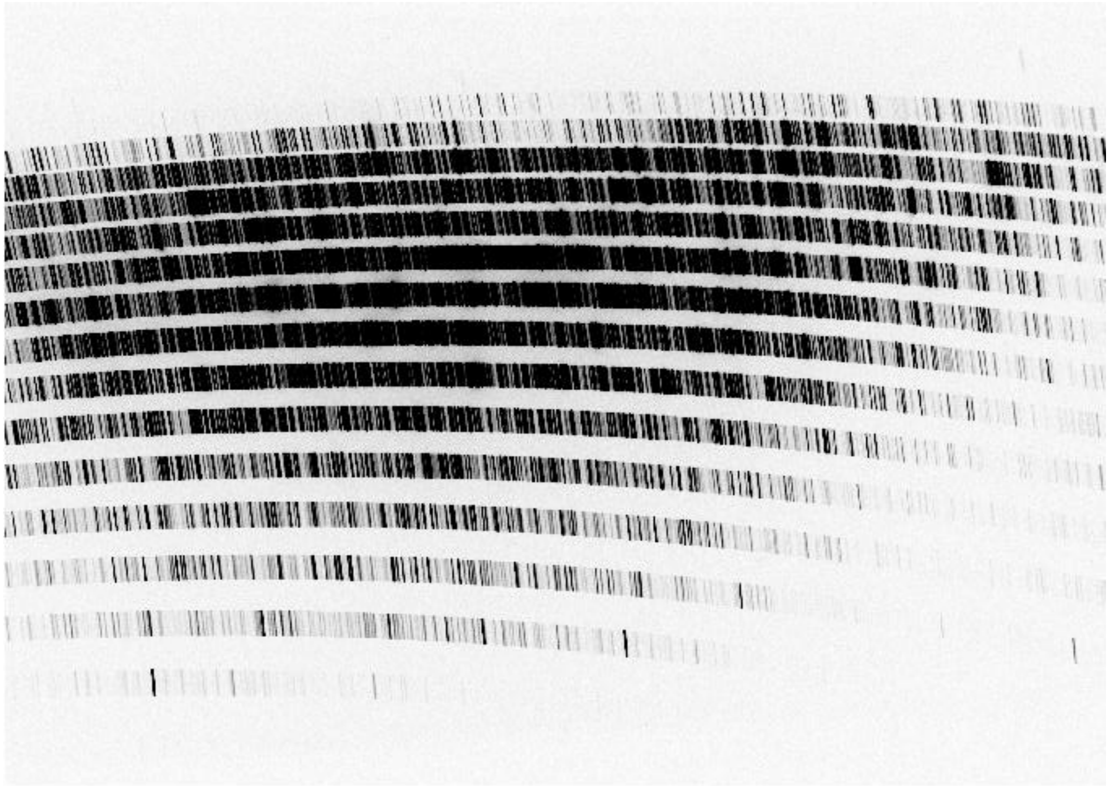
- Overview of X-shooter data set (WD NLTT21844)



UVB arm: orders n=13 to 24, λ= 2940 to 6930**Å.**

Data processing 1.20

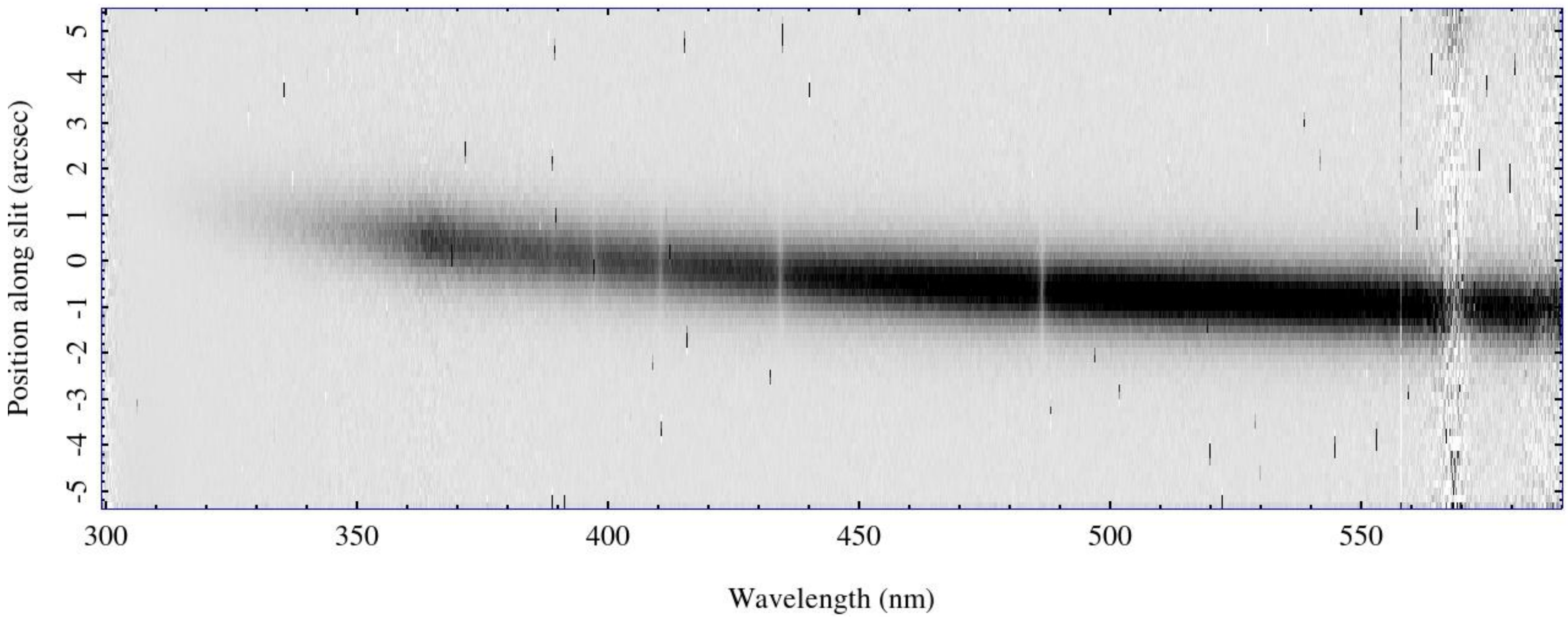
- Overview of X-shooter data set (WD NLTT21844)



ThAr comparison arc in the UVB arm.

Data processing 1.21

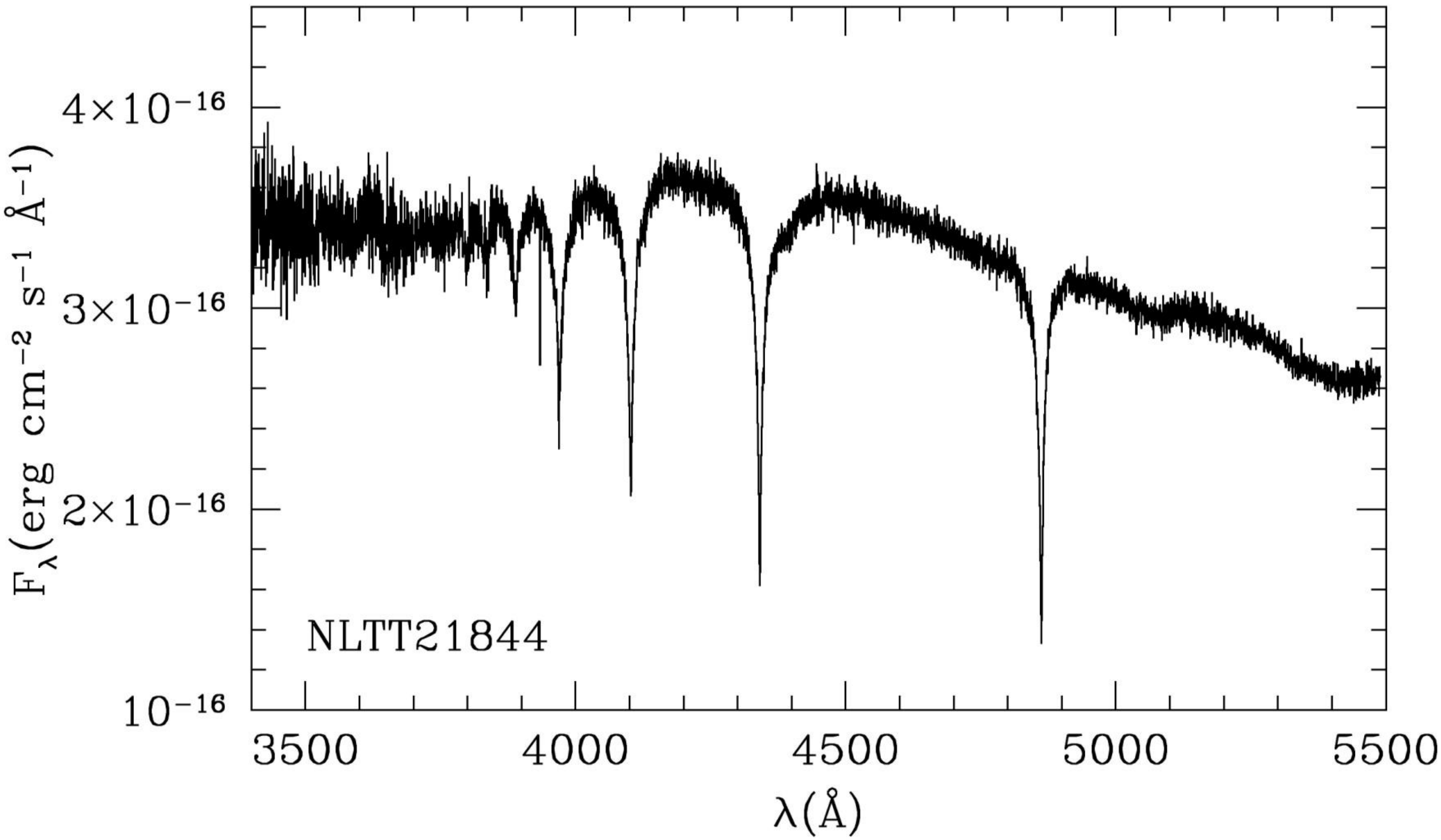
- Overview of X-shooter data set (WD NLTT21844)



Summed orders in the (λ,Sky/slit) plane. The trace shows sky refraction effect.

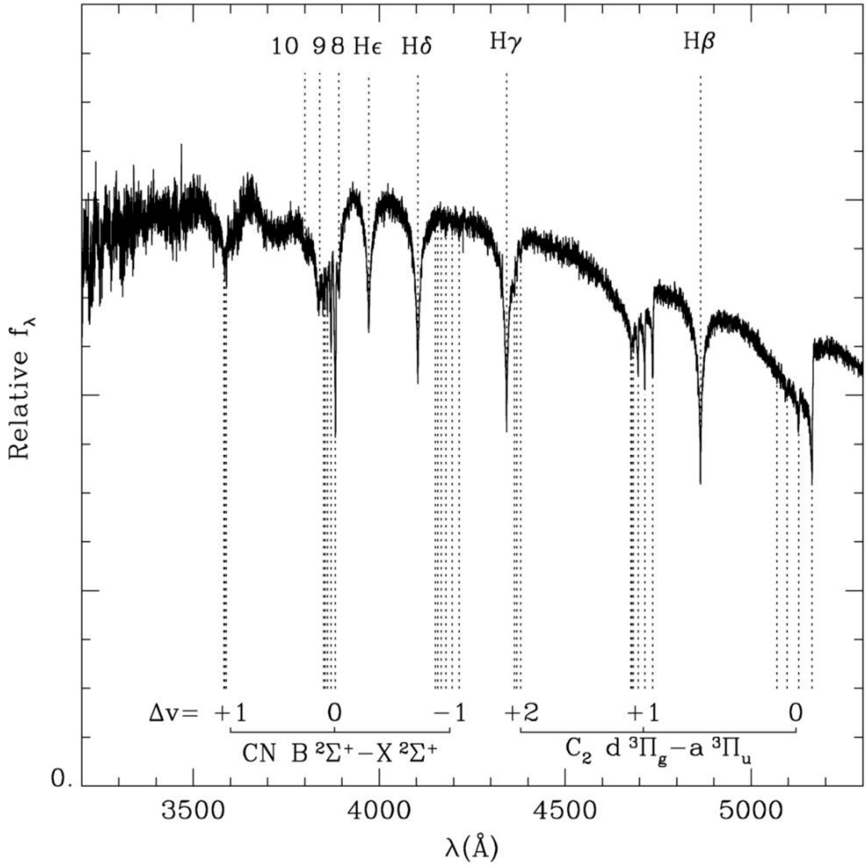
Data processing 1.22

- Overview of X-shooter data set (WD NLTT21844)



Data processing 1.23

- Overview of X-shooter data set: NLTT16249



Science results:

• Detection of CN and C_2 molecular opacity (vibrational bands).

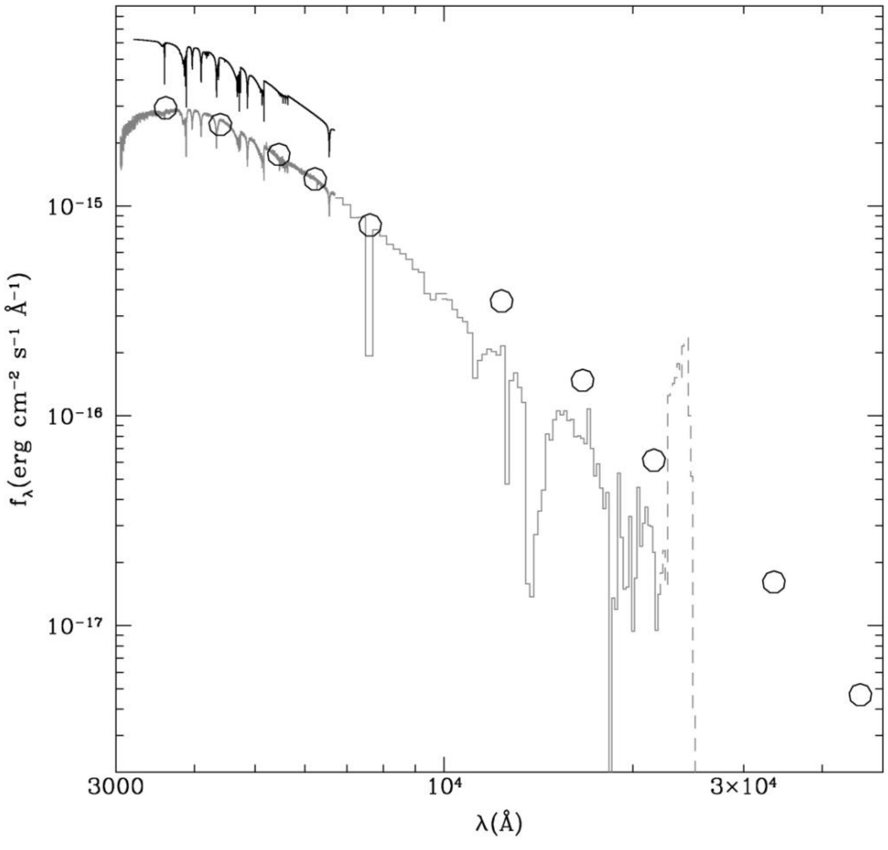
•Precise radial velocity (residuals 2 km/s) reveal a close double degenerate system comprising one H-rich star and a C/He-rich star with traces of nitrogen.

•C and N are dredged-up from the core.

•C/N≈140 is a left over of the AGB at the core-envelope interface.

Data processing 1.24

- Overview of X-shooter data set: NLTT16249

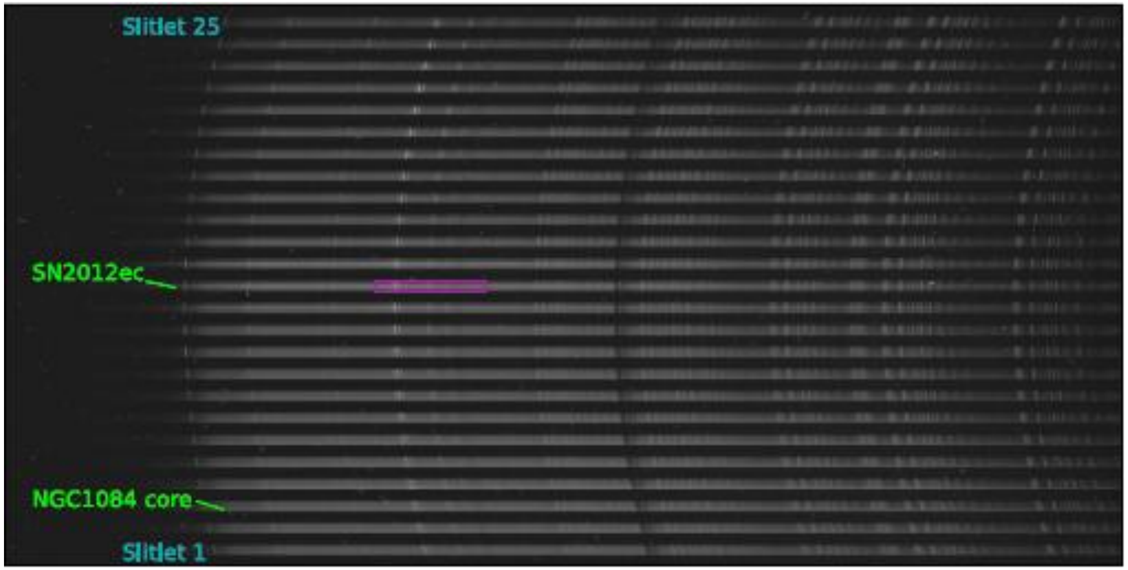


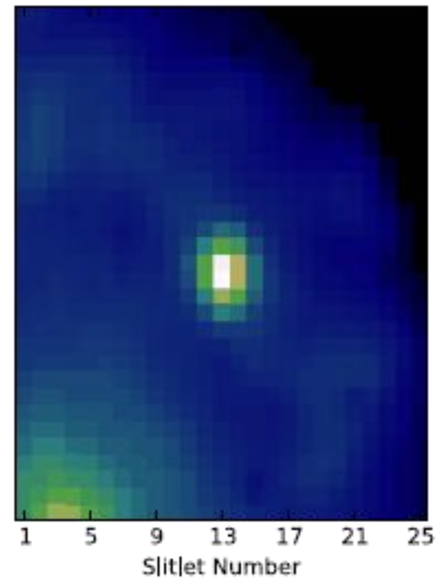
•The Xshooter covers Spectral range from 0.3 to 2.5 μm.

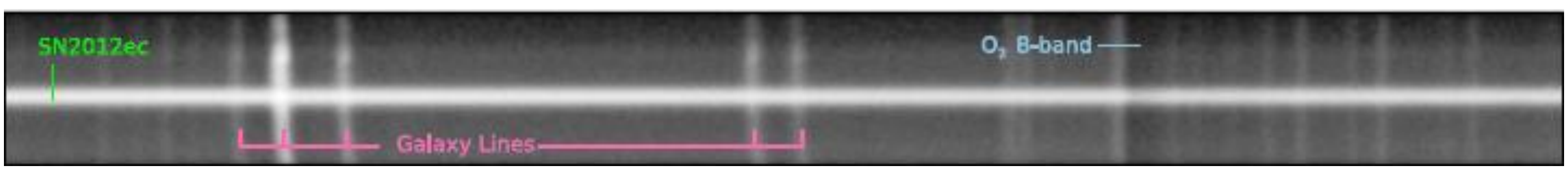
• The spectral energy distribution (SED) reveals two components or nearly equal temperature proving that the two stars are bearly co-eval and left the main-sequence nearly simultaneously from progenitors of equal mass.

Data processing 1.25

- Overview of WiFeS data set (example SN2012ec)

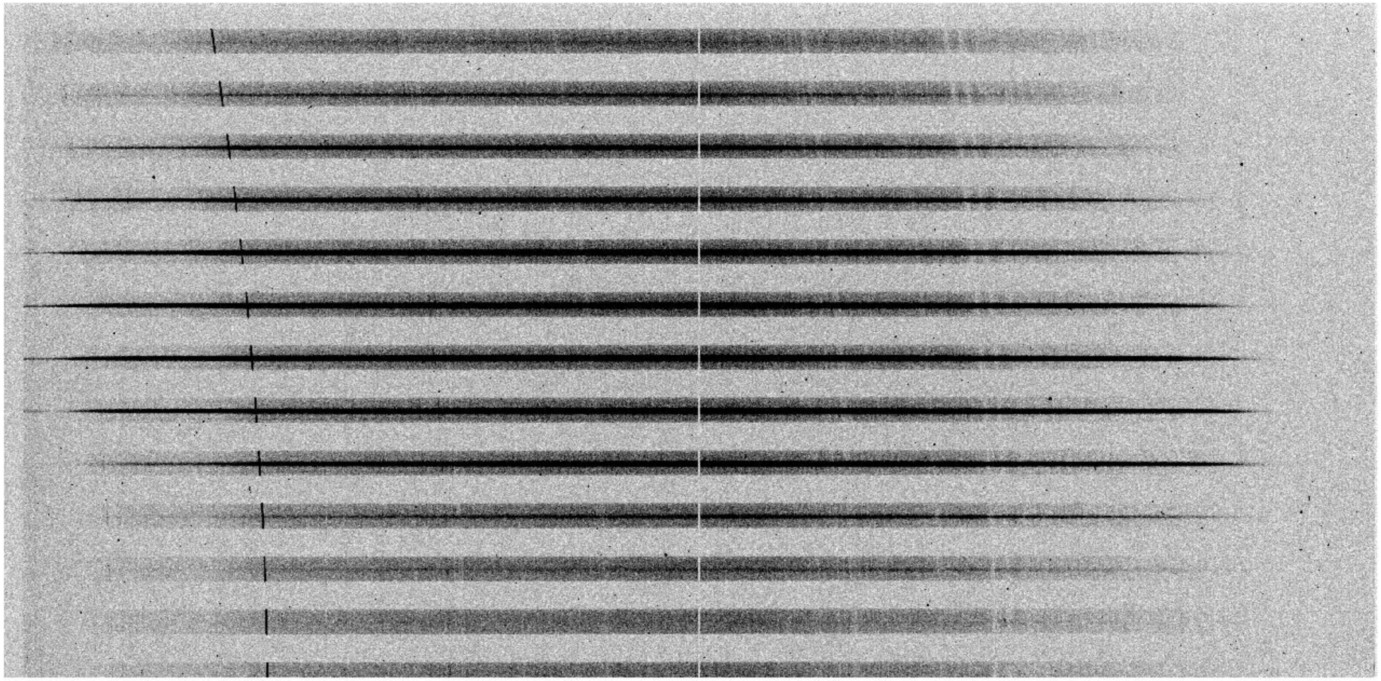






Data processing 1.26

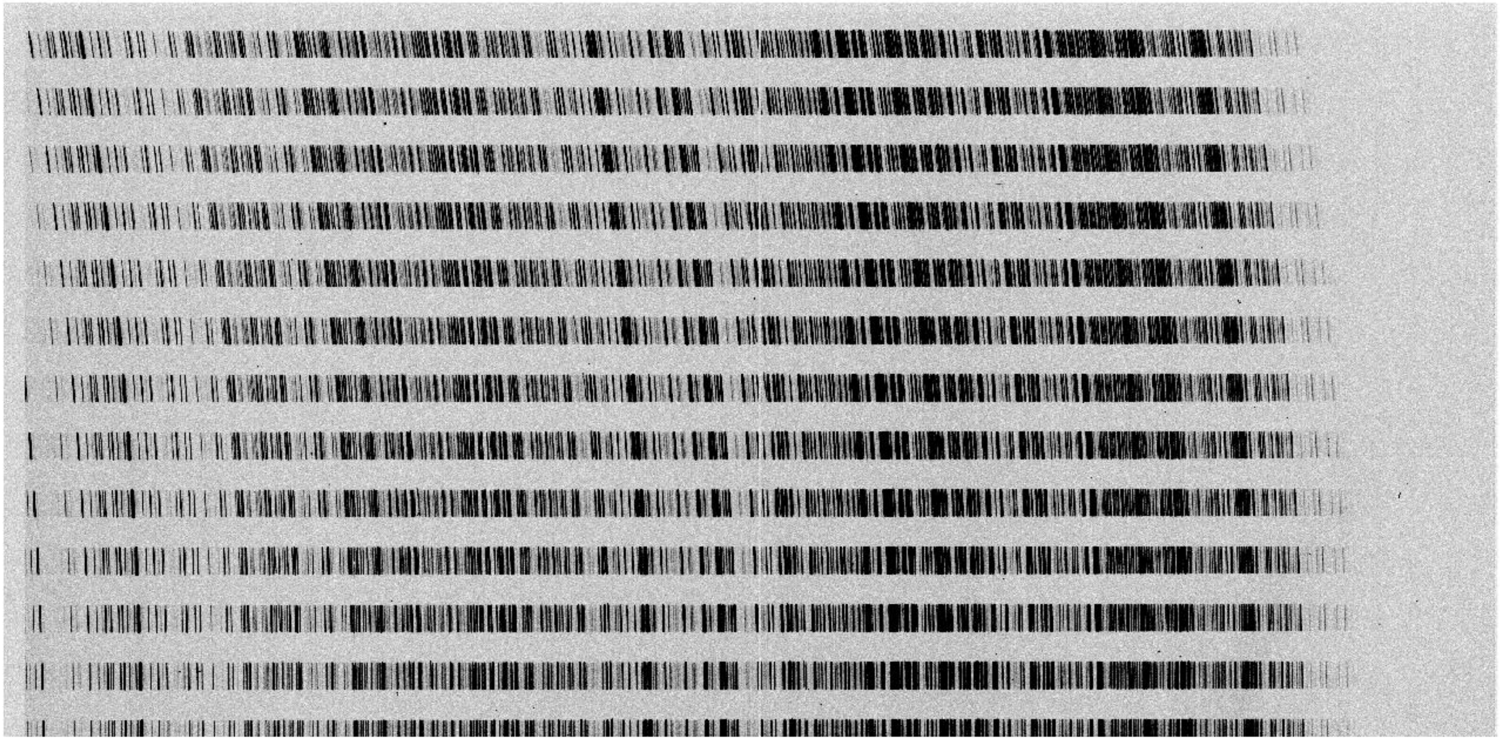
- Overview of WiFeS data set (December 2011)



Each trace corresponds to the star illuminating one of the stacked slits.

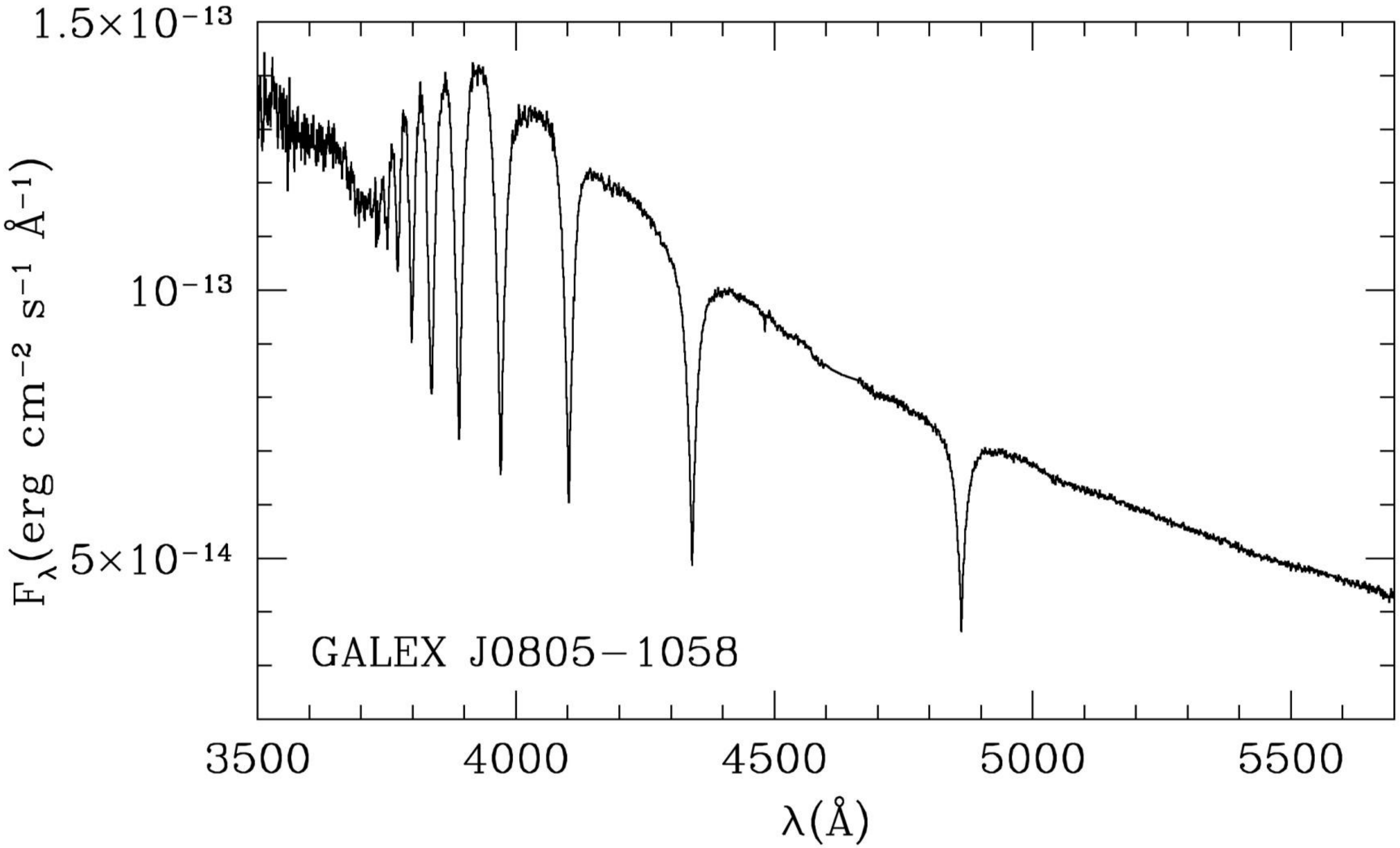
Data processing 1.27

- Overview of WiFeS data set (NeAr comparison)



Data processing 1.28

- Overview of WiFeS data set (published spectrum)



Data processing 1.29

- Overview and summary of data processing
  I. We examined simple techniques applied to long-slit polarization and intensity spectra of a magnetic white dwarf.
  II. These simple procedures were also readily applicable to the WiFeS integral field data.
  III. The X-shooter pipeline employs a full 2D remapping of the aperture using the comparison arc line geometry.
  IV. Examples of extracted data highlight the properties of compact stars (**B**, Z, T)

Final word

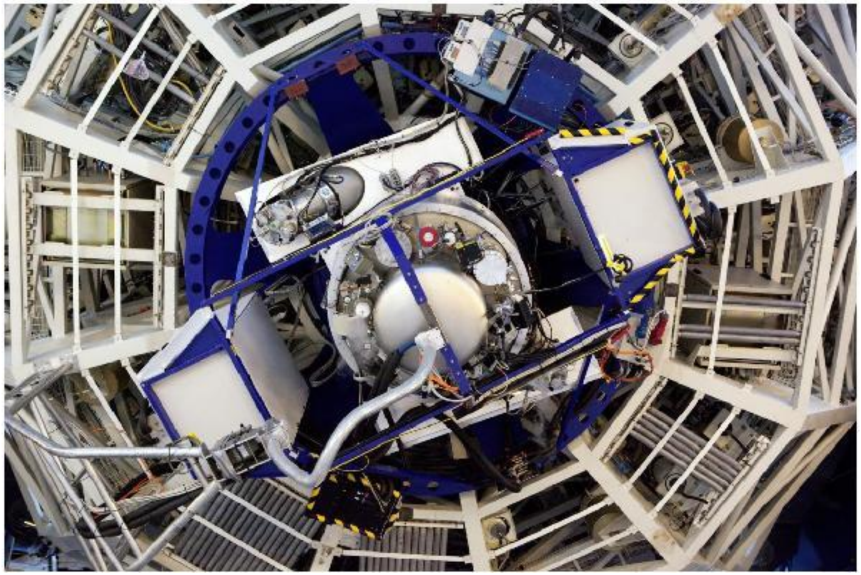
- Basic stellar properties (T,Z,**B**) are measured spectroscopically.
- High quality intensity and polarization spectra of faint stars are collected with spectrographs at 4/8m telescopes.
- Data processing for modern instruments is complex and requires use of reduction pipelines.
- Understanding the basics of data processing remains essential to evaluate the products delivered by these pipelines.

Focal Reducer and low dispersion Spectrograph (FORS)

- Visual and near-UV spectrograph mounted on the Cassegrain focus of the VLT (UT1)
- Long-slit spectroscopy, multi-object spectroscopy, spectropolarimetry
  - wavelength range: 3300 to 11000 Å
  - $R = \lambda/\Delta\lambda \approx 250 - 2500$
- Imaging:
  - Standard resolution: FoV - 6.8′x6.8′, 0.125″/pixel
  - High Resolution: FoV = 4.2′x4.2′, 0.063″/pixel

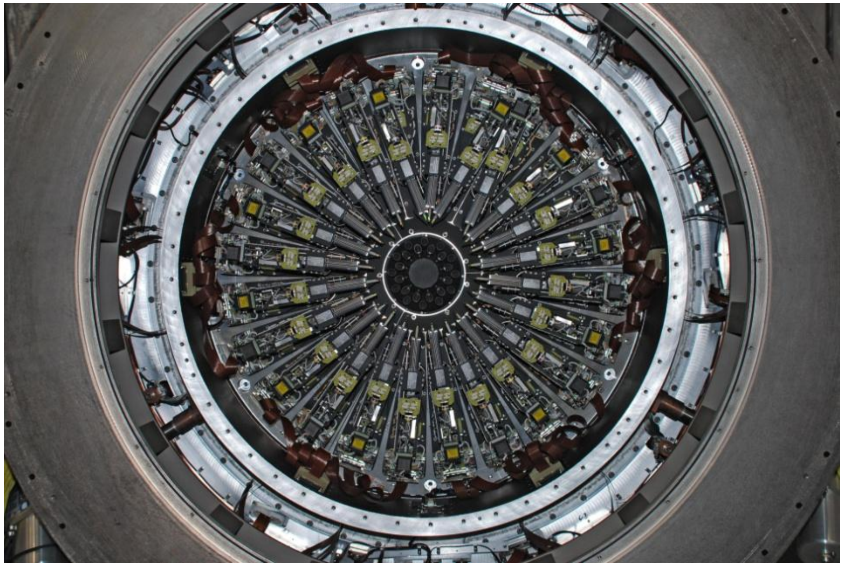
XSHOOTER

- A multi wavelength medium resolution spectrograph attached to the VLT (UT2) Cassegrain focus.
- Consists of 3 spectroscopic arms:
  - UVB: 3000 – 5595 Å
  - VIS: 5595 – 10240 Å
  - NIR: 1.024 – 2.48 μm



- Slit-spectroscopy: Depending on the slit-width: $R = \lambda/\Delta\lambda \approx 3000 – 18000$ Å
- Integral field unit: 4″x1.8″

K-band Multi Object Spectrograph (KMOS)



- KMOS is attached to the Nasmyth focus on the VLT (UT1)
- Capable of simultaneously obtaining infrared spectra of 24 targets
- Makes use of 24 configurable arms that feed the light into IFUs
  - IFU: 2.8″x2.8″
- Wavelength range: 0.8 – 2.5 μm
- $R = \lambda/\Delta\lambda$ = 2000 – 4200
- Patrol field: 7.2 arcmin diameter

Essential References

- Gray, D.F. 1976, The Observation and Analysis of Stellar Photospheres, Wiley-Interscience
- Gray, D.F. 1992, The Observation and Analysis of Stellar Photospheres, Cambridge
- Pradhan, A.K. & Nahar, S.N. 2011, Atomic Astrophysics and Spectroscopy, Cambridge
- Gray, R.O. & Corbally, C.J. 2009, Stellar Spectral Classification, Princeton
- Hubeny, I. & Mihalas, D. 2014, Theory of Stellar Atmospheres, Princeton