Introduction to high resolution spectroscopy

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Outline

- General introduction to spectroscopy
- Why is high spectral resolution interesting?
- How to obtain high spectral resolution
  - Échelle gratings
- How to obtain high precision

- Reducing high resolution (échelle) spectra
- Some examples of science with high spectral resolution

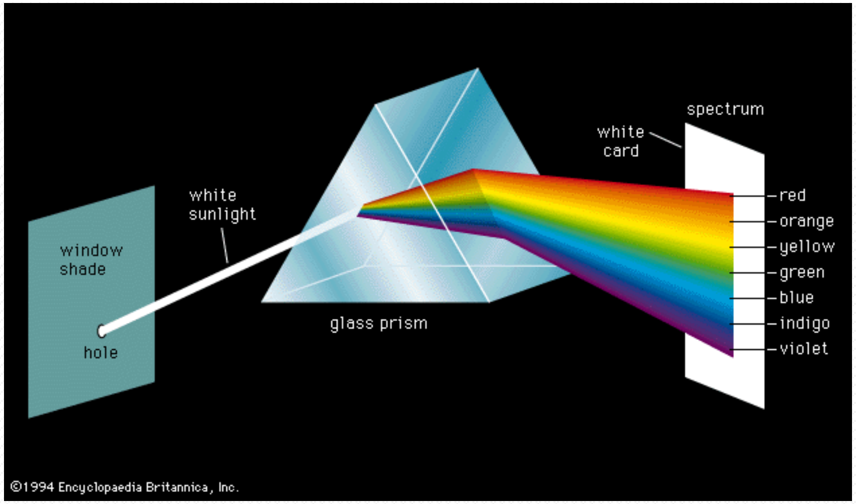
Spectroscopy

- Spectral analysis is probably the most important method for learning about the physics of astronomical sources
- Simplest method to get spectral information is using filters
- In this case the size of the spectral element we can resolve is the width of the filter
- More detailed information is obtained if the light is sent through a dispersive element

Dispersive elements

- The core optical element of an astronomical spectrograph is its dispersive element
- With a dispersive element, the angle at which the light leaves it, is wavelength dependent.
- There are two kinds of dispersive elements:
  - Prisms
  - Grating

Newton's experiment:



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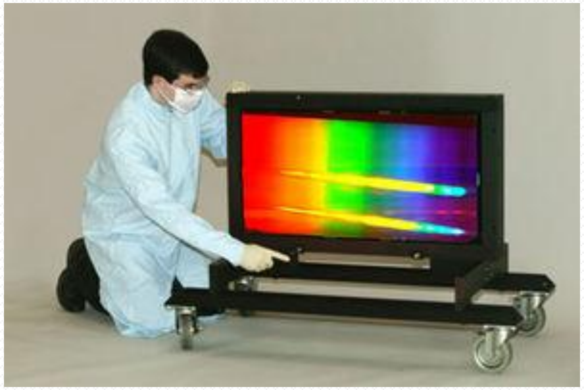
Gratings



Grating equation: $m\lambda=\sigma(\sin\beta + \sin\alpha)$

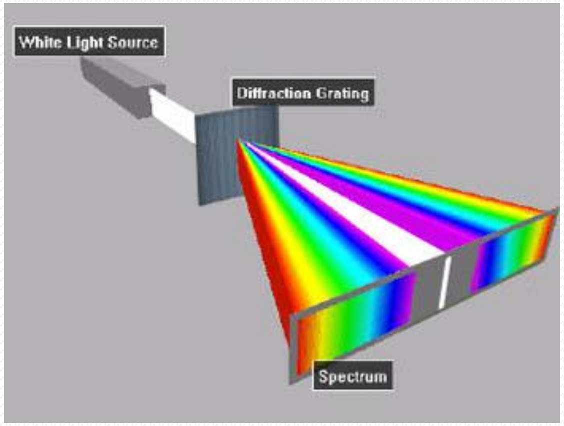
m=order number

λ=wavelength

σ=distance between grooves/slits

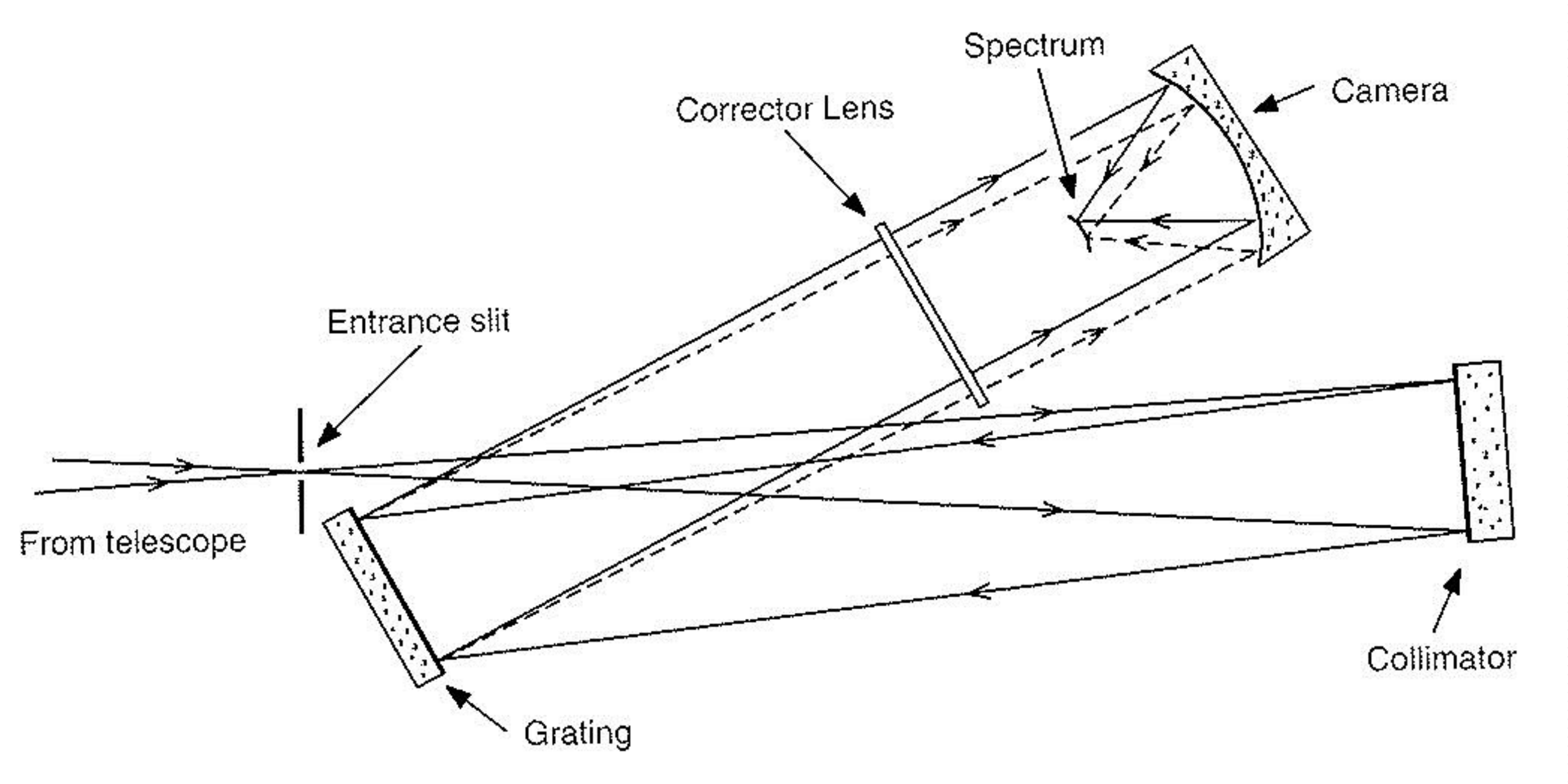
β=angle of diffraction

α=angle of incidence



The spectrum is repeated in the different orders of diffraction.
Only the zeroth order spectrum is pure white.
Two colours of different orders may overlap if their angles of diffraction are equal.

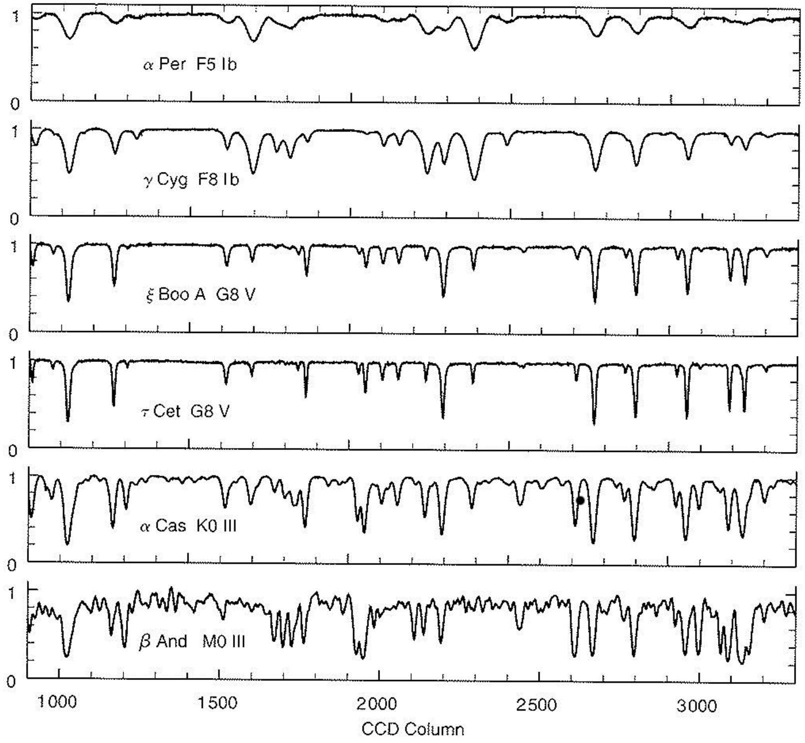
Spectrograph



Resolution of a prism is low compared to what is possible with a grating large enough to accept the same beam diameter, therefore grating is usually the primary dispersive element in a modern spectrograph.

High resolution spectroscopy

- For seeing detailed structures in our spectra one resolution element has to be small, i.e., the spectral resolution has to be high
- With high spectral resolution we can for example study in detail stellar atmospheres, or composition of the interstellar medium



23Å of stellar spectra centered at λ6245Å

Resolving power

- Resolving power (R) tells how small details we can resolve in the spectrum

- It is defined as $\lambda/\Delta\lambda$

- So for example:
  - R=1000 at 6500 Å gives $\Delta\lambda$=6.5 Å or ~ 300km/s
  - R=10 000 at 6500 Å gives $\Delta\lambda$=0.65 Å or ~30km/s
  - R=100 000 at 6500 Å gives $\Delta\lambda$=0.065 Å or ~3km/s

- Note that the resolution in velocity does not change:

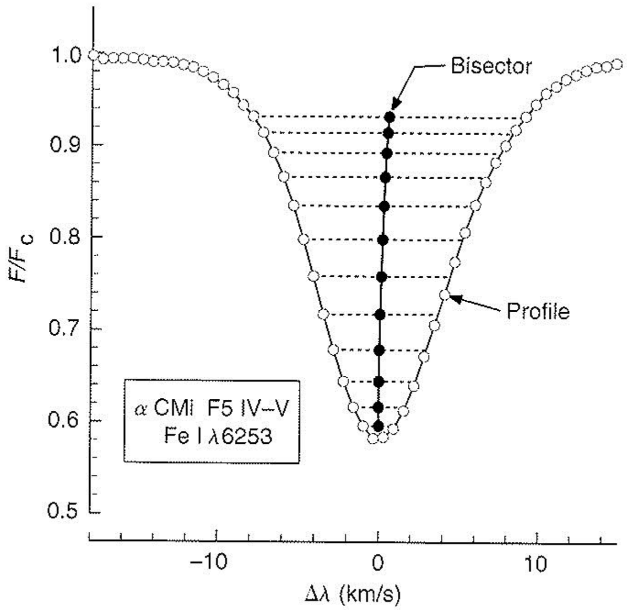
  - $R=\lambda/\Delta\lambda=c/\Delta v$

Which resolving power to use for your observations?

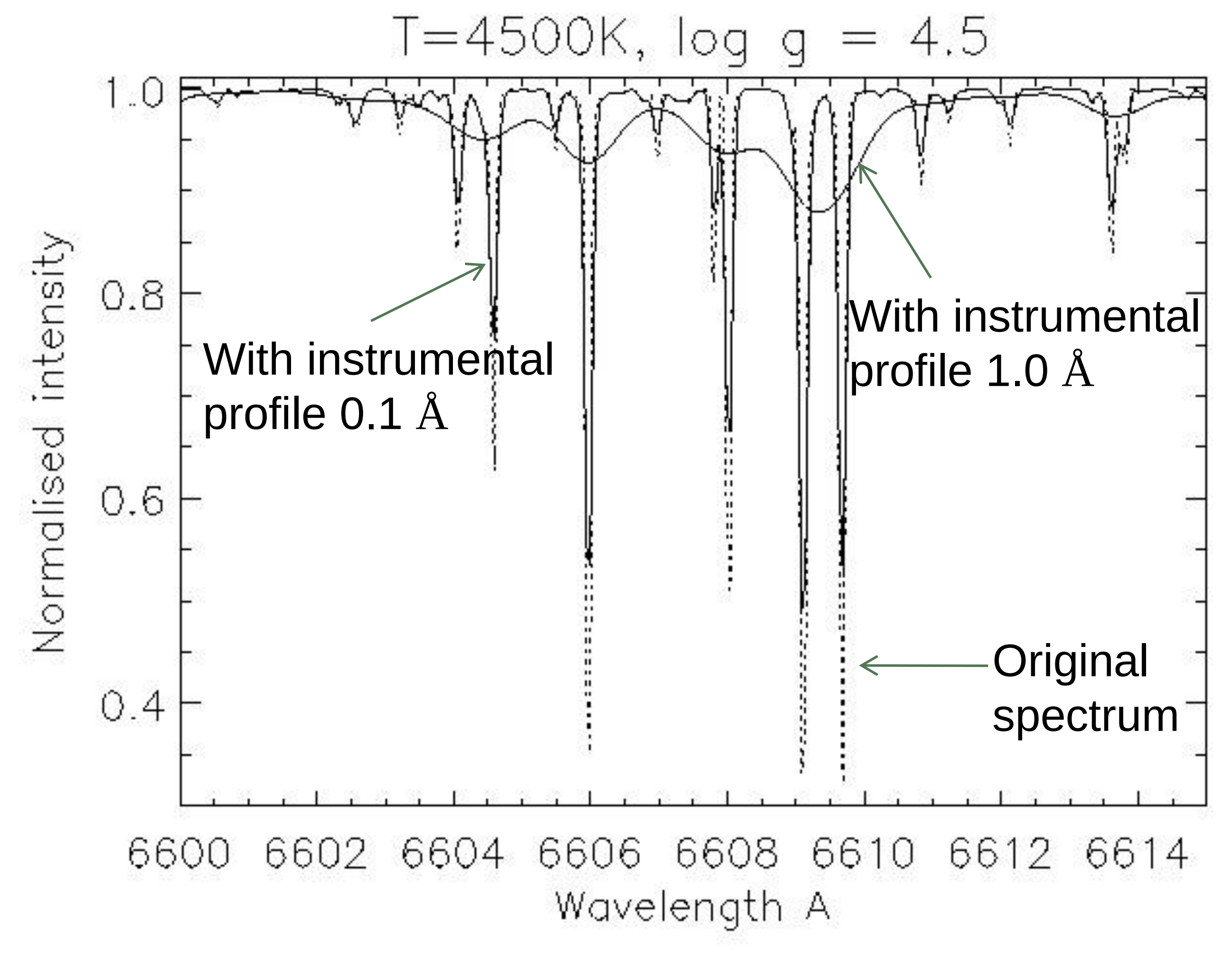
- Always „the larger the better“ is not the answer
- High resolution needs a lot of photons, so to get any signal one needs a bright source and/or a large telescope
- Also, in some cases there is no need for high resolution. If the process you want to study produces velocities of 1000 km/s, there is not much point studying it with resolution of 1 km/s
- Still, with high resolution you might discover surprising things about your object

Line bisectors

- One good example of importance of high resolution when studying stellar atmospheres are the line bisectors
- The asymmetrical line bisector in cool stars rises from velocity fields in the atmosphere
- Can be seen only when the resolving power of the instrument is > 100 000



Lines get “diluted” by low resolution



With instrumental profile 0.1 Å

With instrumental profile 1.0 Å

Original spectrum

Angular dispersion

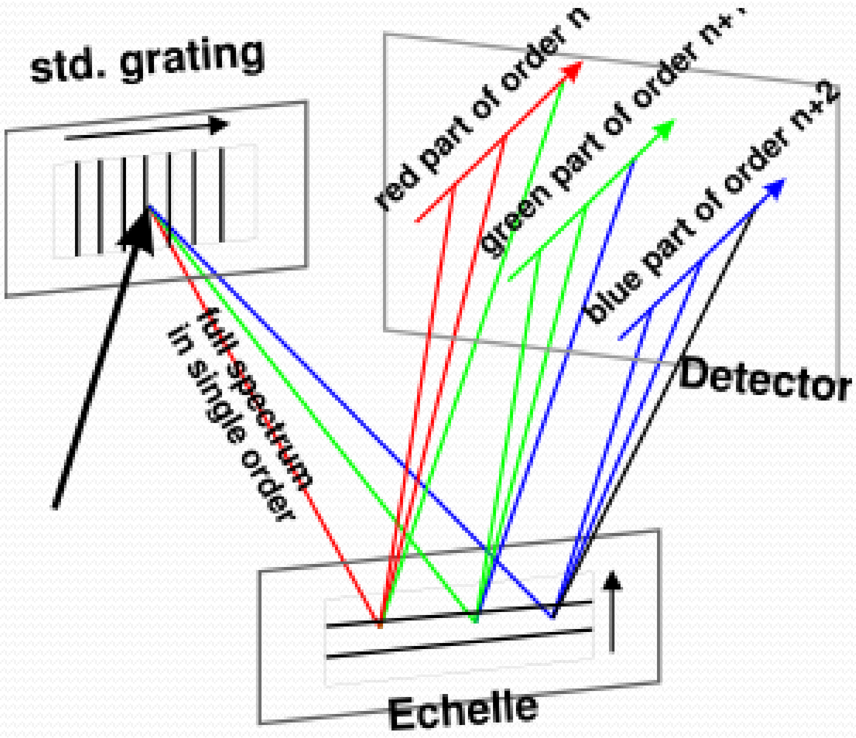
$$A = m/(\sigma \cos \beta) \quad (1)$$

$$A=(\sin \beta + \sin \alpha)/(\lambda \cos \beta) \quad (2)$$

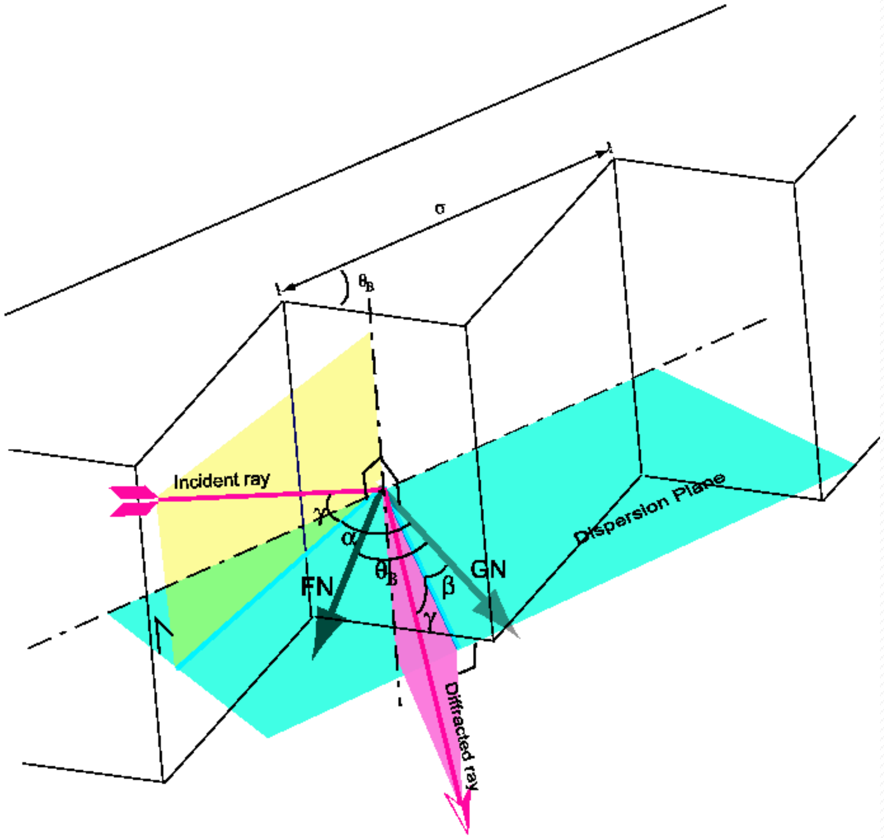
- From (1) we see that the angular dispersion A in a given order m is a function of grating constant σ and diffraction angle β
- This means that for changing the A we either choose grating with different groove/slit spacing or change the angle of diffraction
- From (2) we can also see that the A is given by angle of incidence α and angle of diffraction β at given wavelength, independent of m and σ. Thus a given angular dispersion can be obtained with many combinations of m and σ, provided that the angles at the grating are unchanged and m/σ is constant.
- Recognising this lead to the development of coarsely ruled reflection gratings specifically designed for high angular dispersion by making α and β large, typically about 60°. → **échelle gratings**

Échelle grating 1

- For high resolution astronomical work échelle is the preferred choise over a grating used in low order
- The reasons for this are:
  - Two dimensional format that permits broad spectral coverage
  - Allows compact spectrograph design
- Échelle has a large groove spacing and is used at high order number, thus it is necessary to use a cross-disperser to separate the orders, or to use a filter to isolate a single order



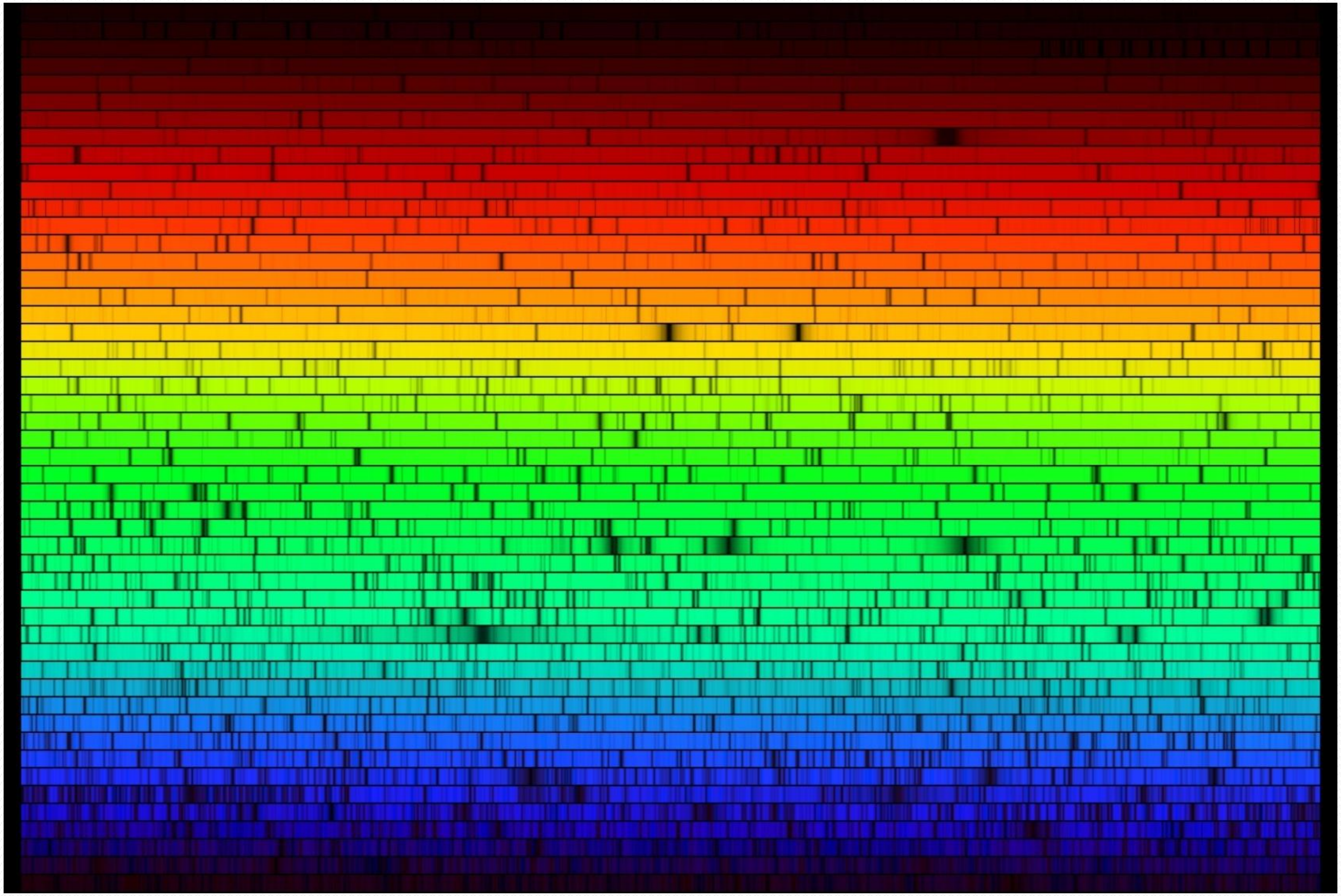
Échelle grating 2



GN: Grating Normal, FN: Facet Normal
α: Incident Angle, β: Diffraction angle, γ: Out-of-Plane Angle
σ: Groove Spacing, θ_B: Blaze Angle

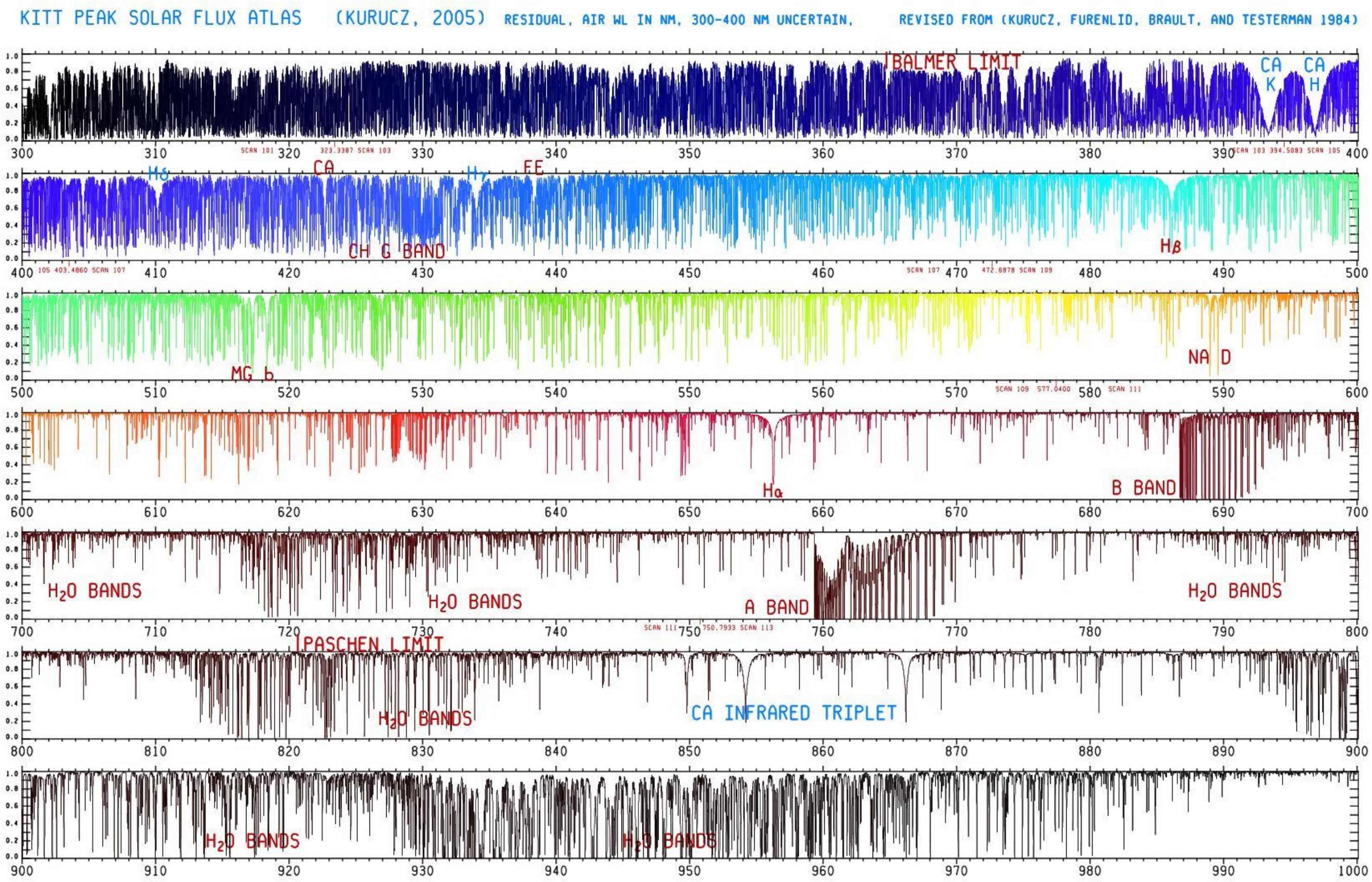
- Two design parameters define blazed gratings:
  - Groove frequency
  - Blaze angle
- Blaze angle tells how much the facet normal is tilted in comparison to the grating normal
- Échelle gratings are often defined by „R number“, i.e., blaze angle of R4 is $\tan(76^{\circ})=4$

Échelle spectrum



N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

And when unstacked

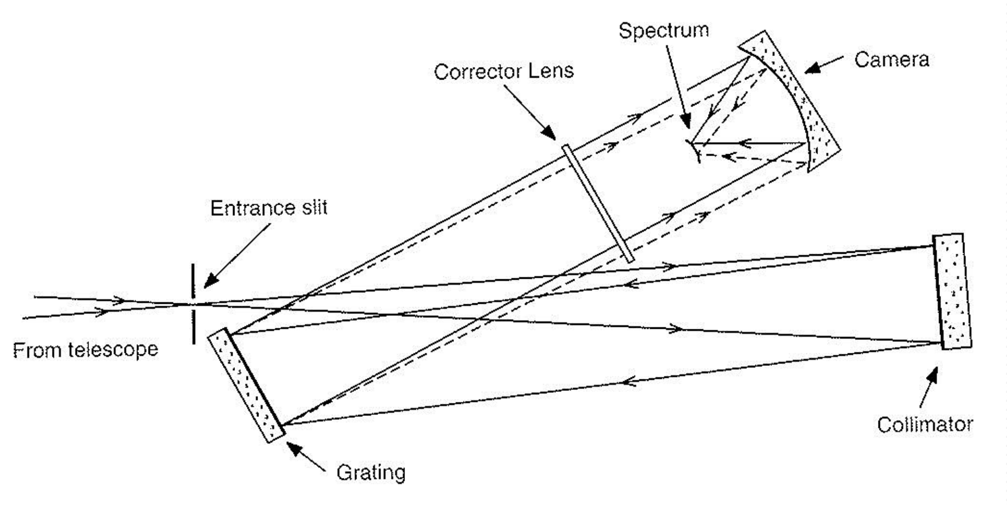


Kitt Peak Solar Flux Atlas, Kurucz 2005

Large telescope, large spectrograph

In the seeing limited domain, if we double the telescope diameter, we must double the slit width to let the same fraction of light through.

Thus, to keep the same two wavelengths non-overlapping in the focal plane of the spectrograph, we must double all dimensions.



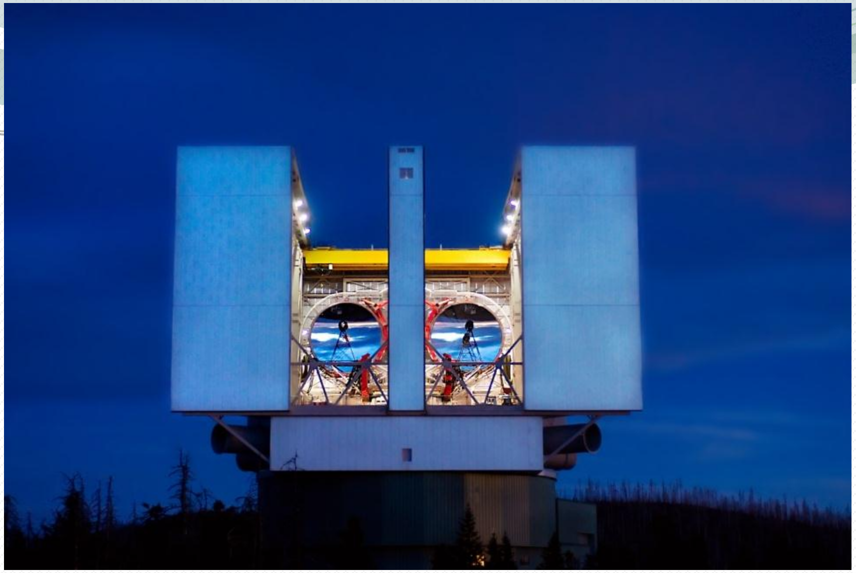
Different in the diffraction limit:

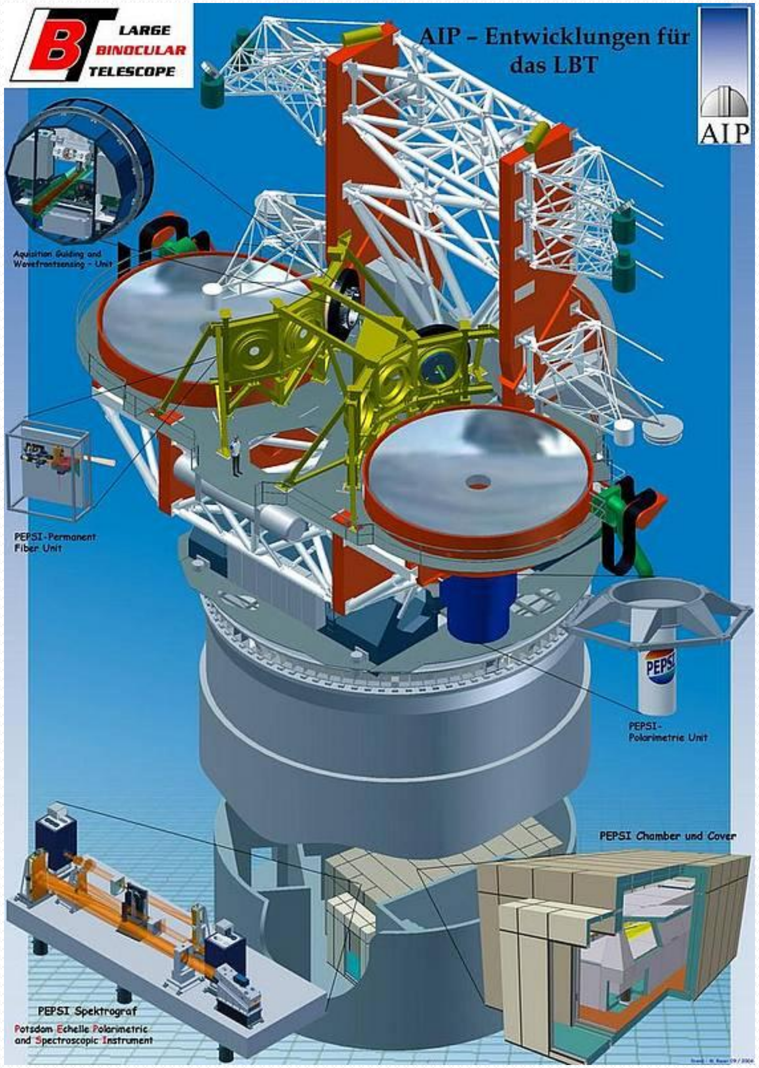
Image size = λ/D_tel * f_tel

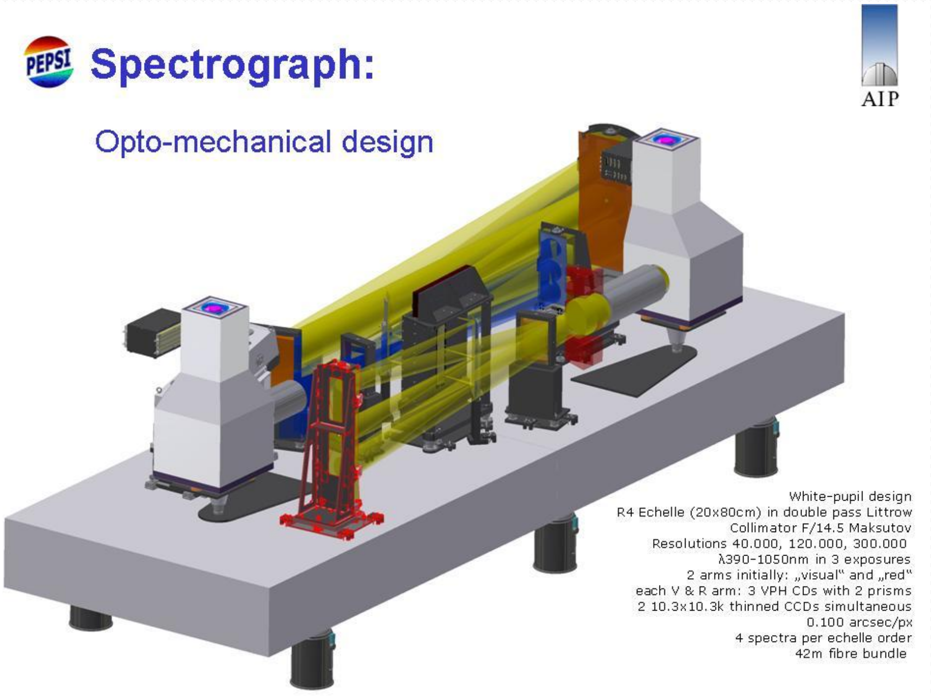
For constant f/D (telescope f ratio) Image size, and hence slit size is independent of telescope diameter.

To first order, spectrograph size scales with telescope size!

PEPSI @ LBT





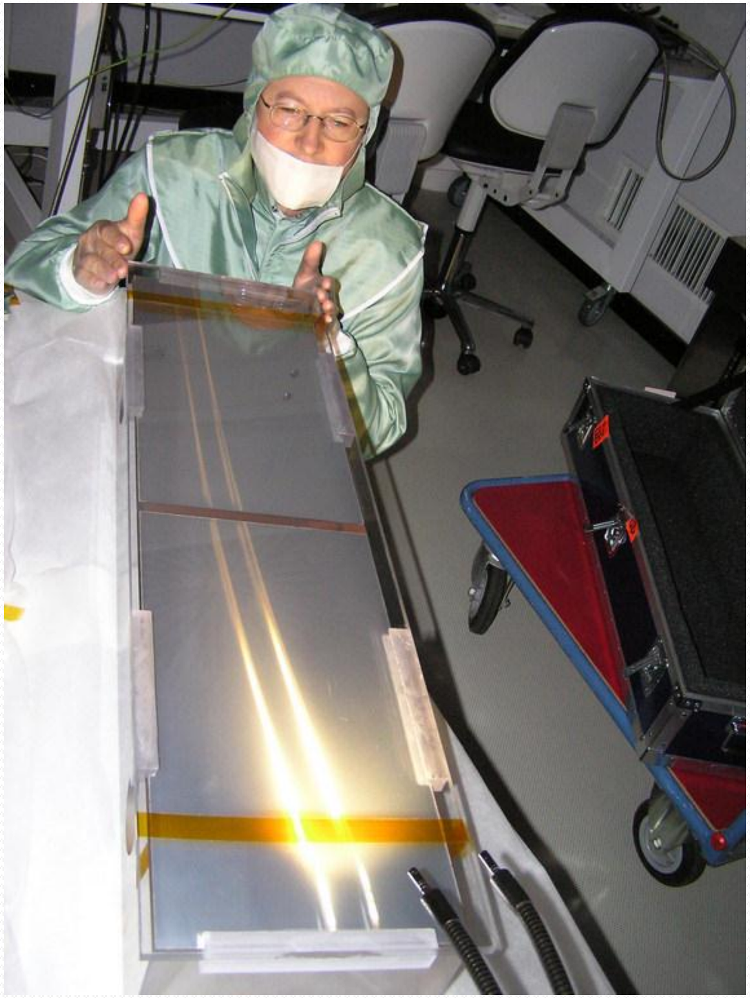


Spectrograph:

Opto-mechanical design

White-pupil design
R4 Echelle (20x80cm) in double pass Littrow
Collimator F/14.5 Maksutov
Resolutions 40.000, 120.000, 300.000
λ390-1050nm in 3 exposures
2 arms initially: „visual“ and „red“
each V & R arm: 3 VPH CDs with 2 prisms
2 10.3x10.3k thinned CCDs simultaneous
0.100 arcsec/px
4 spectra per echelle order
42m fibre bundle

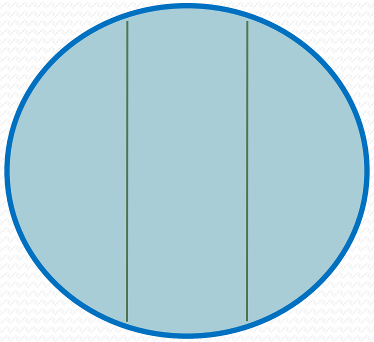
Large components



PEPSI collimator: blank diameters:
M1 = 88cm and M2 = 70cm

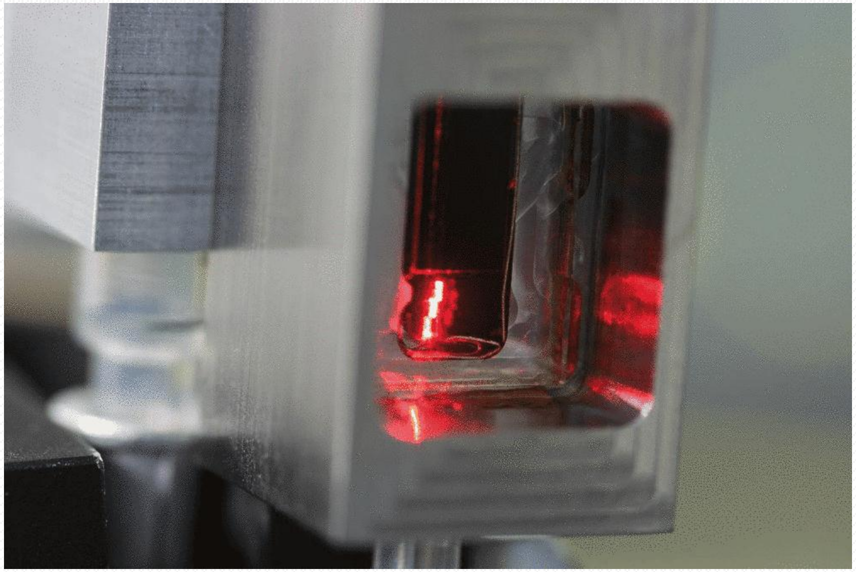
⇦ PEPSI R4 échelle grating 800x200mm

Image slicer



The output from a fiber can be sliced and then put on top of each other on the CCD to increase the resolution

PEPSI image slicer

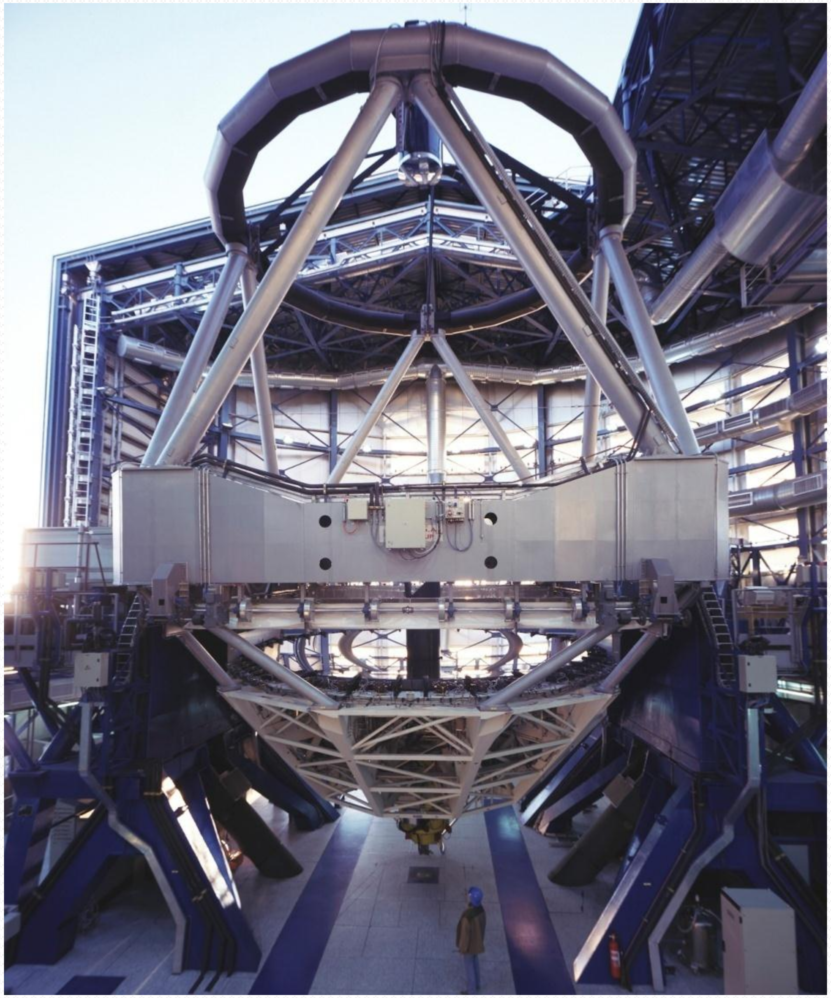


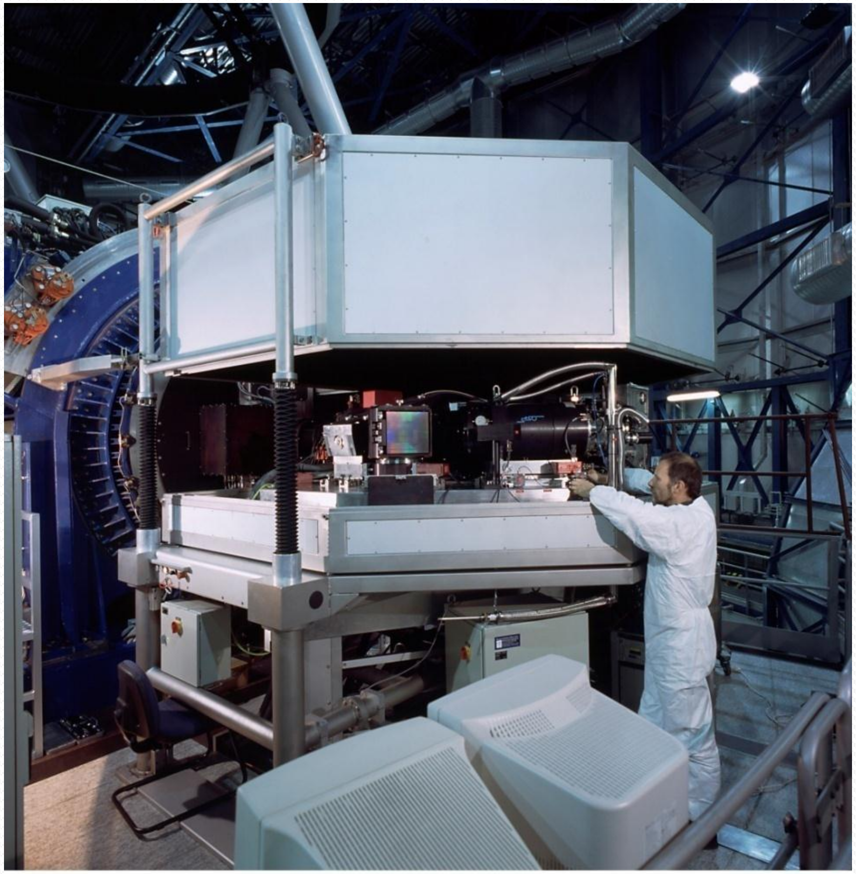
In short, image slicers can increase the resolution without decreasing the efficiency (by much), but the penalty is larger cross dispersion in an échelle spectrograph.

High resolution spectrographs at ESO Paranal

- CRIRES @ Antu (UT1)
  - R = 100 000
  - Spectral range 1 – 5 µm
  - Uses AO to optimise the signal-to-noise ratio and the spatial resolution
- UVES @ Kueyen (UT2)
  - R = 80 000/100 000
  - 3200 – 11000 Å
  - Blue and red arm

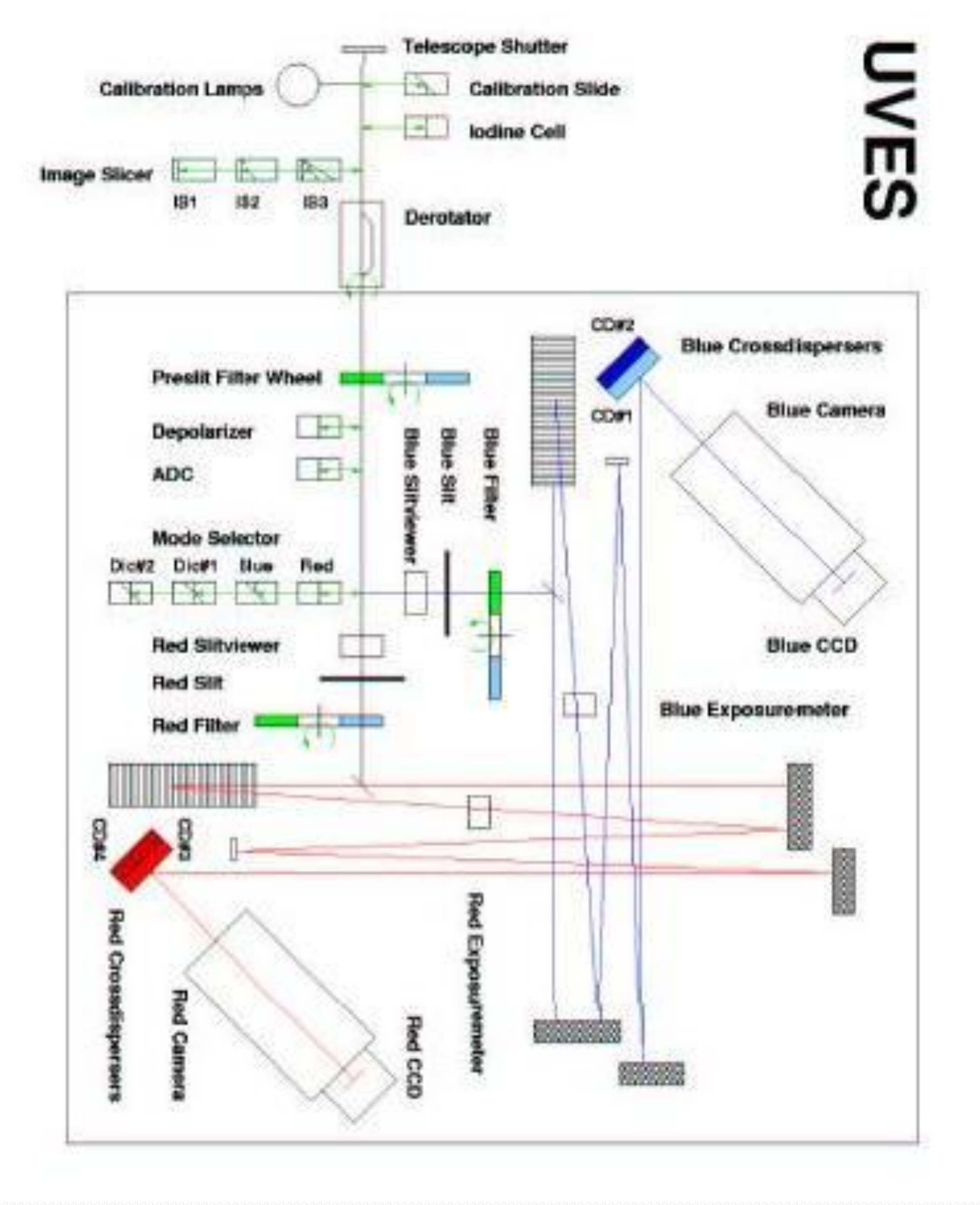
UVES





UVES at Kueyen

ESO PR Photo 43e/99 (8 December 1999)

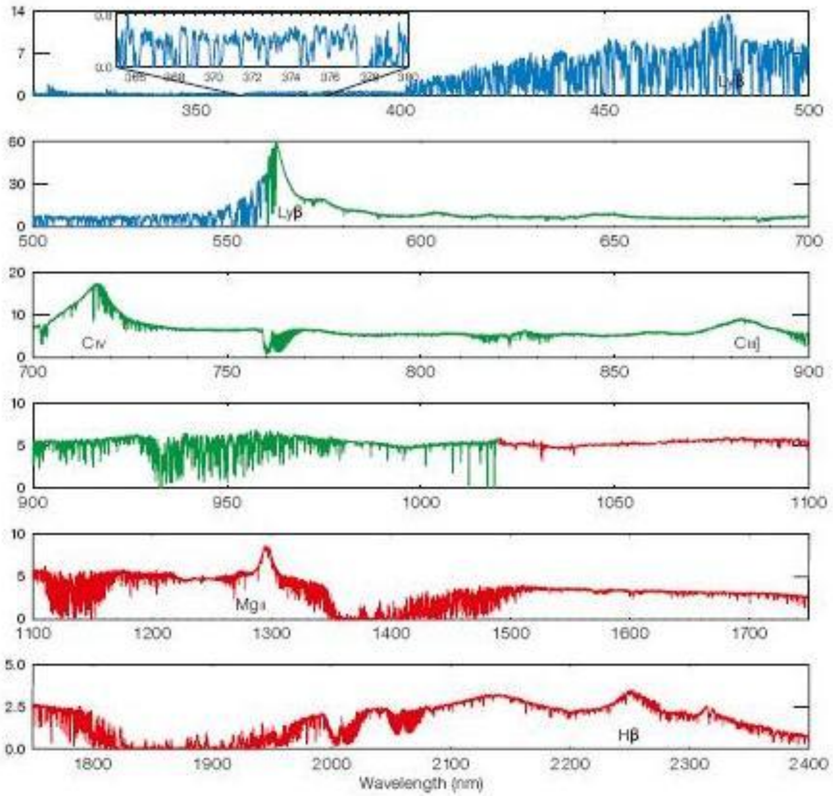


UVES is a so-called “white pupil” spectrograph, where a second collimator mirror allows placing the pupil image on both the échelle and the cross-disperser gratings, thus minimizing the size of the spectrograph camera optics

X-Shooter

Wavelength range from atmospheric cutoff in UV to 2.4 microns

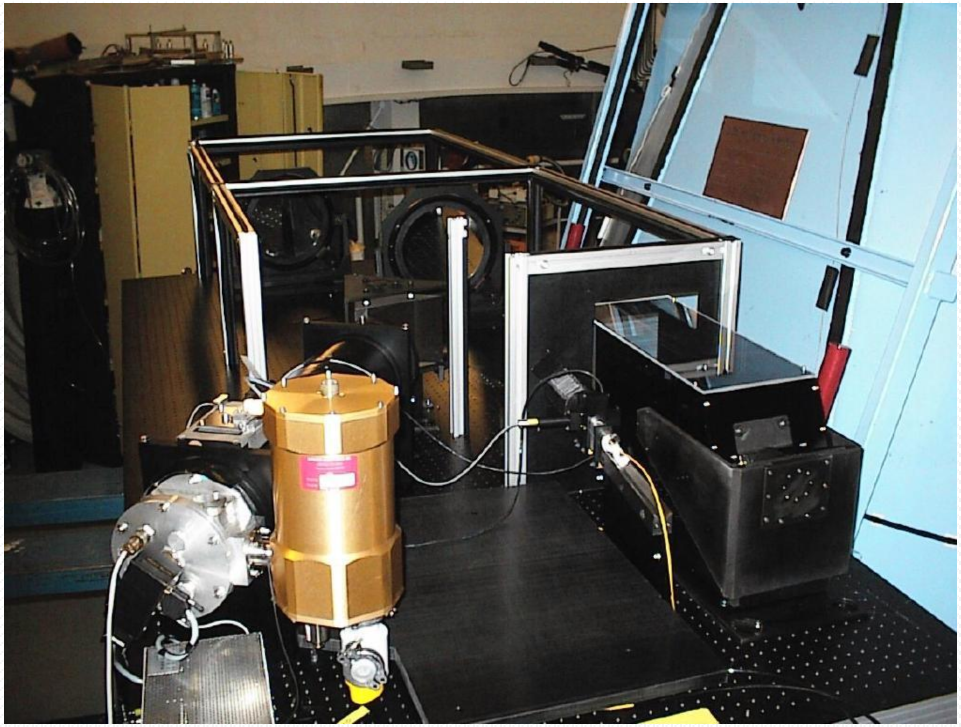
Intermediate resolution, up to 17 000



High resolution spectrographs at Nordic Optical Telescope

- FIES
  - R=40 000 & 60 000
  - 4000-8300 Å in a single setting
  - Mounted in a well insulated building
- SOFIN
  - R=30 000, 80 000 &

    170 000
  - 3500-11000Å
  - Also specctropolarimetry

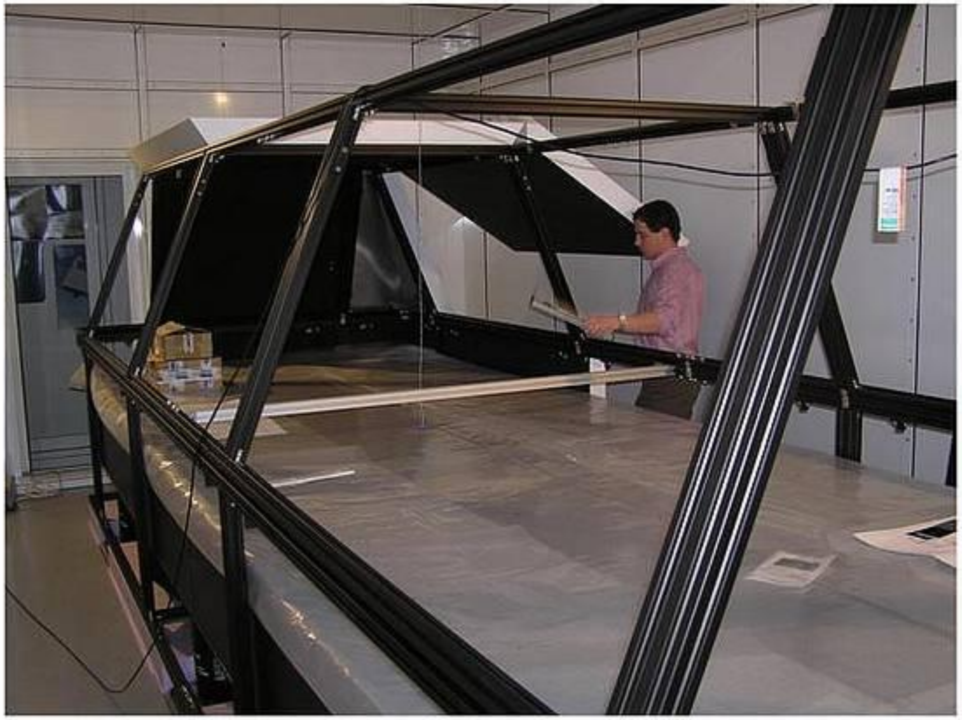


FIES spectrograph

Obtaining high precision

- For some work one also needs high precision, for example when studying extra solar planets based on radial velocities
- This means that the spectrograph environment should be very well controlled.
- Even small changes in gravity (orientation of the spectrograph), temperature and pressure change the behaviour of the spectrograph, not to mention vibrations caused by external (or internal) sources

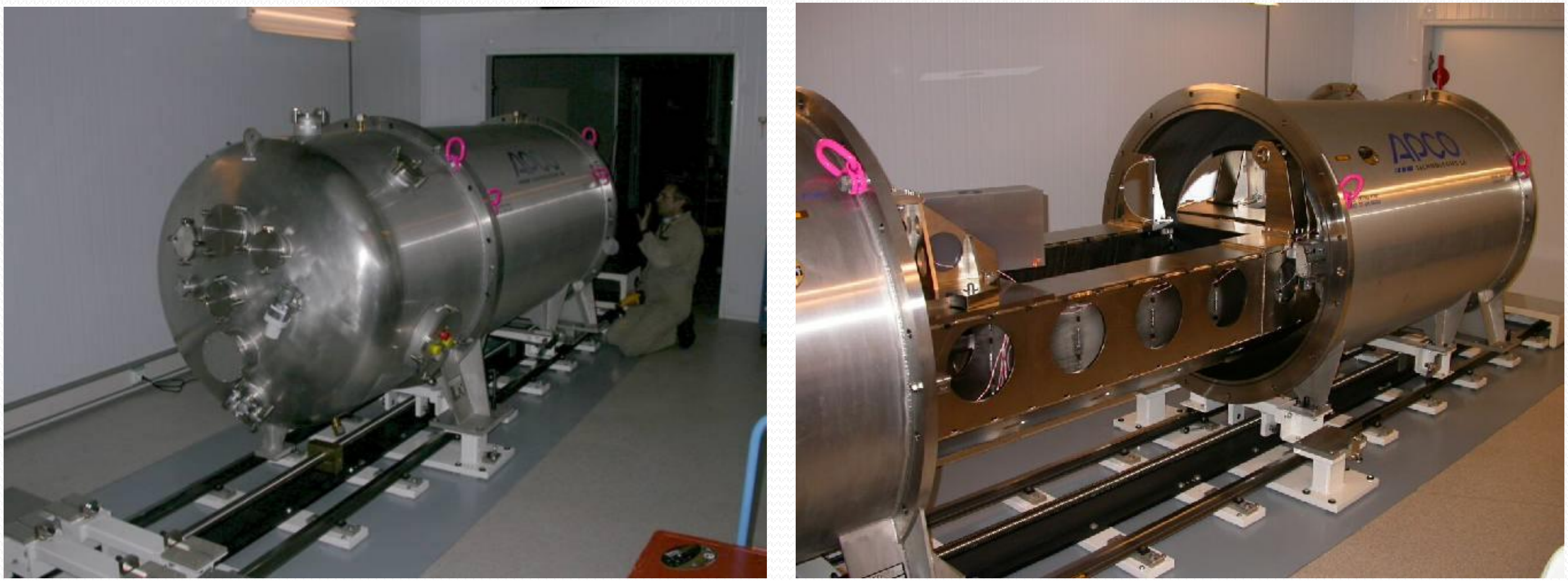
Optical table assembly



xyz gas-supports >10Hz

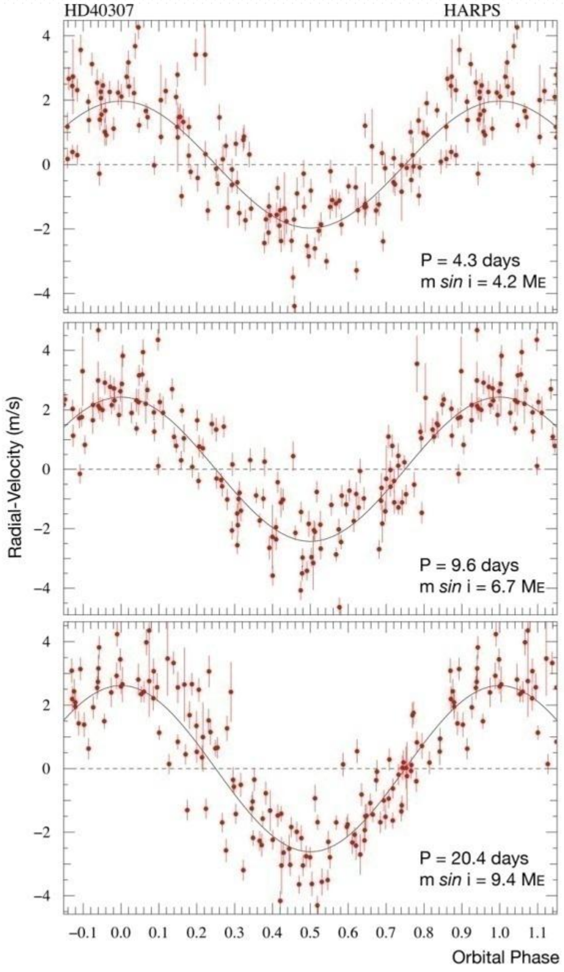
<10Hz damping pads
(carbon-bubble foam)

HARPS, the ultimate planet finder



3 Super Earths

- The HARPS discovery of trio of “super” Earths
- Planets with mass 4.2, 6.7 and 9.4 Earth masses orbit one star
- With periods of 4.3, 9.6 and 20.4 days

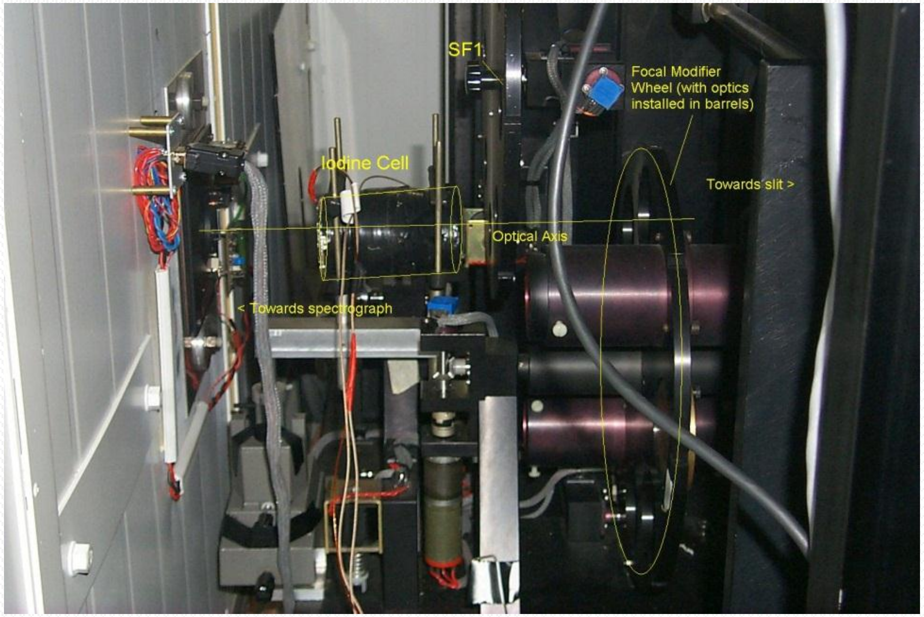


Measurements of HD 40307
(HARPS/3.6-m)

ESO Press Photo 19b/08 (16 June 2008)

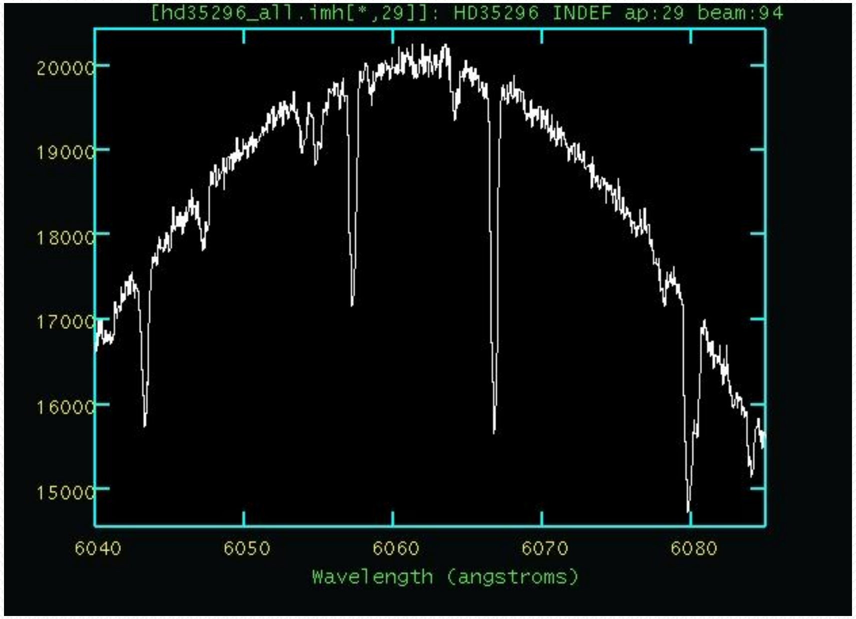
Iodine cell

- Used for high precision work, like extra-solar planets and asteroseismology
- The cell is a sealed glass cylinder with iodine crystals
- When heated above 35 C iodine becomes gaseous
- Starlight passing through the cell gets absorbed by the iodine gas and this produces many sharp absorption lines between 4800-6000 Å
- These sharp absorption lines allow VERY accurate velocity measurement

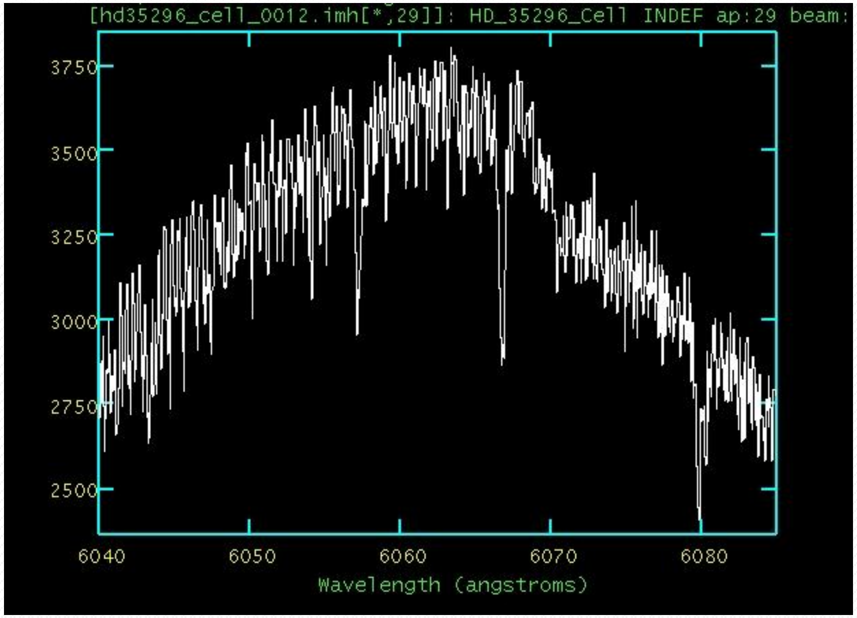


Iodine cell 2

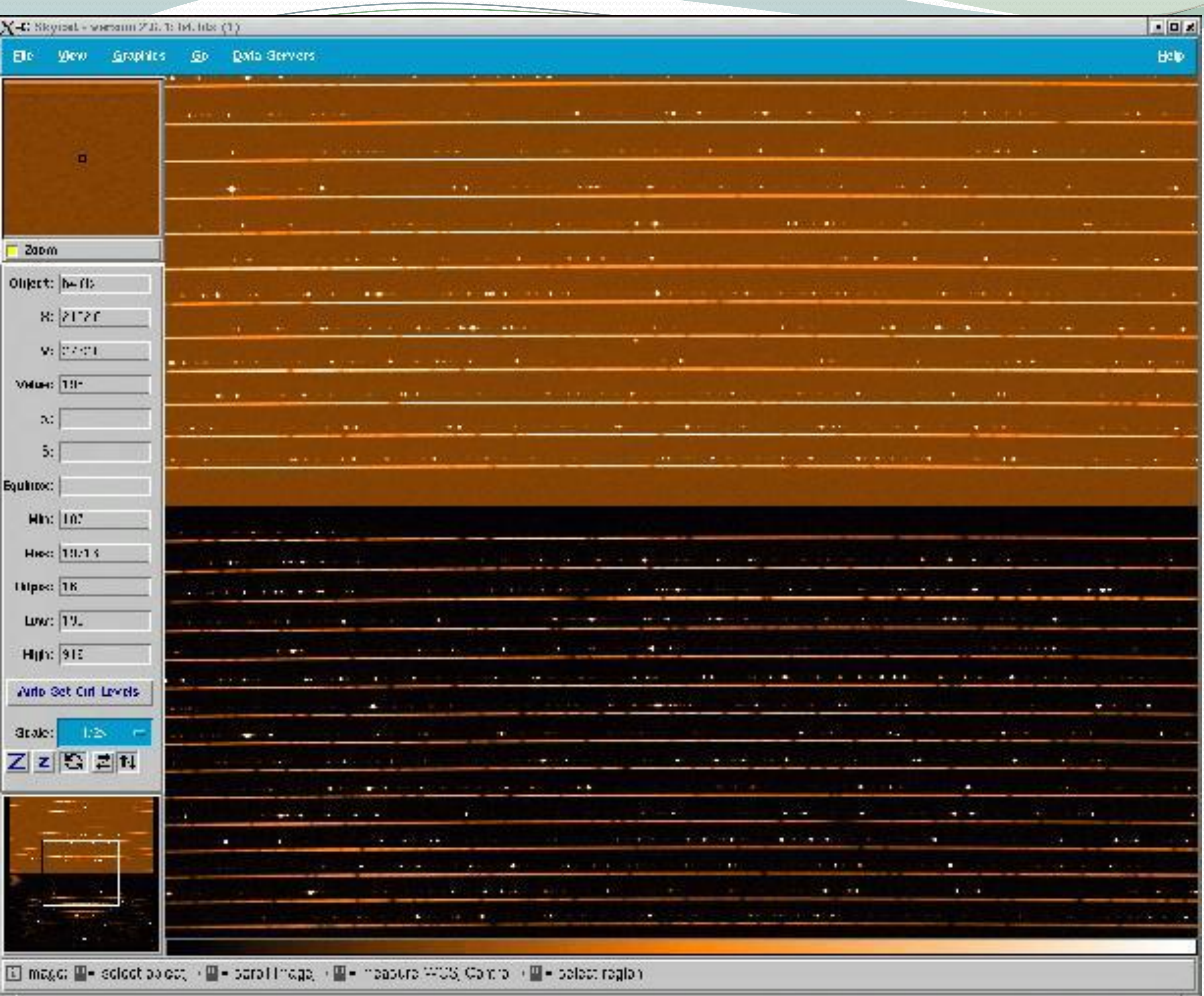
Without



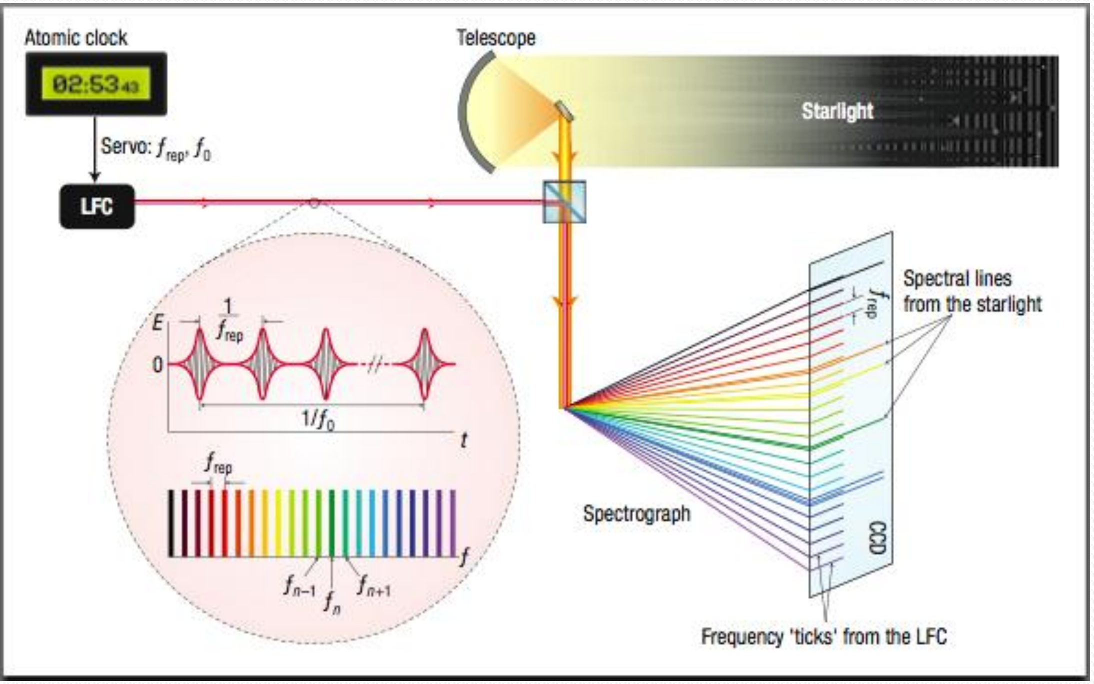
With



Simultaneous ThAr



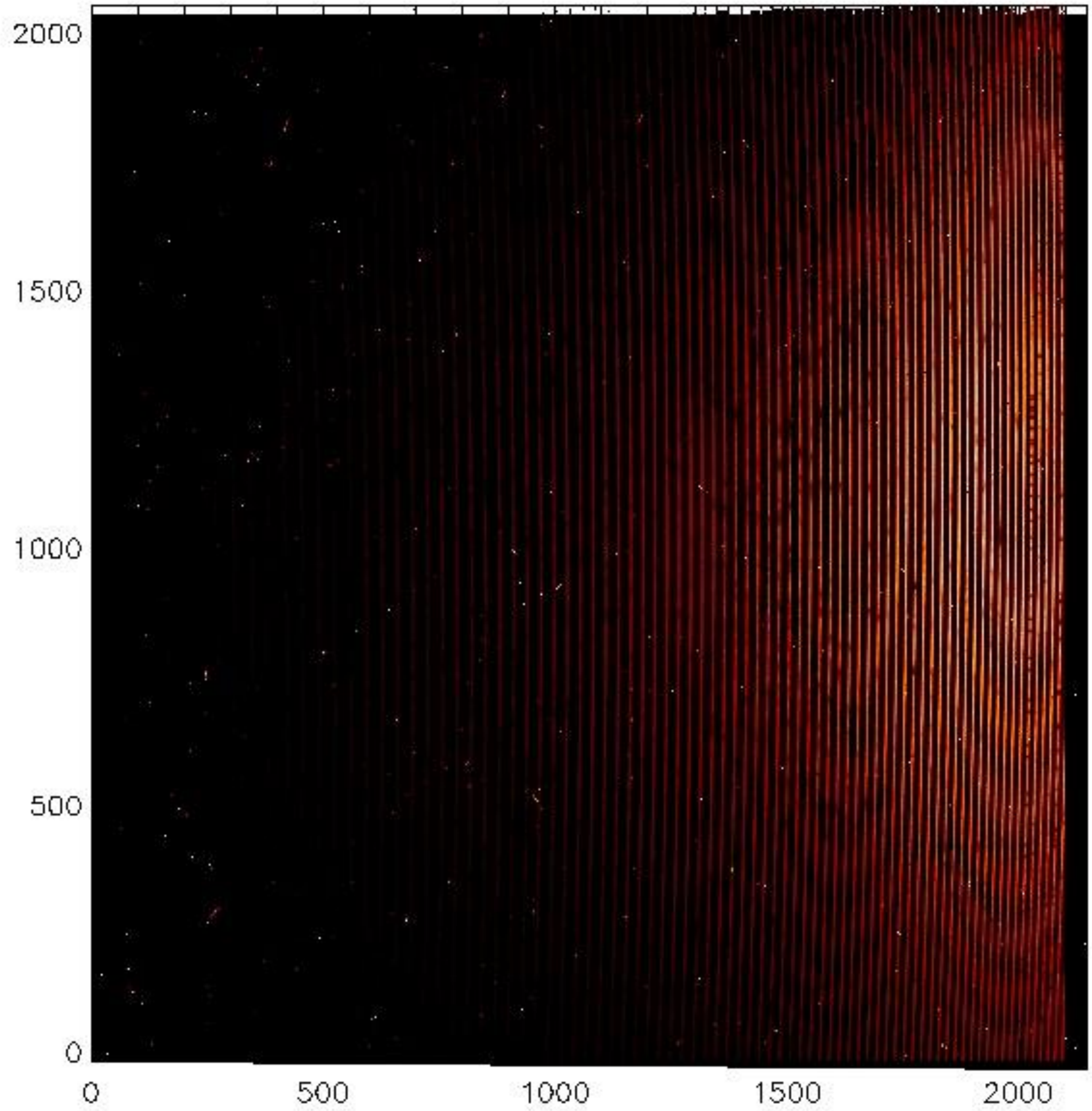
Laser frequency comb



- Tomorrow’s tool for high precision measurements
- Uses ultra-short pulses of laser light to create a 'frequency comb' - light at many frequencies separated by a constant interval
- Test system yielded 9m/s at 1.5μm

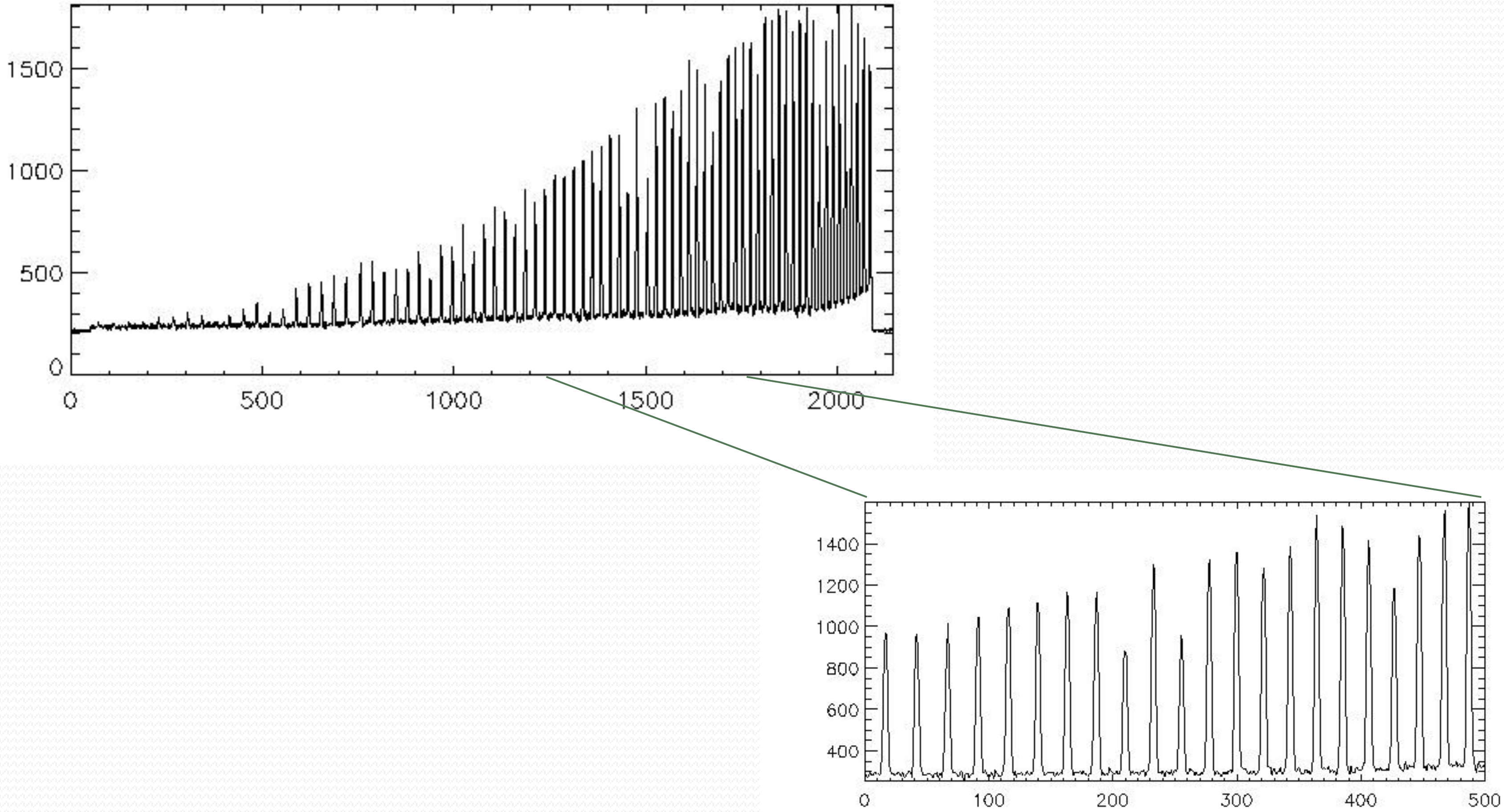
Reduction steps

- Removal of bias
- Correction with the master flat field
- Evaluation and removal of background/scattered light
- Definition of spectral orders
- Extraction of the orders
- Correcting the shape of the order using flat field
- Wavelength calibration
- Heliocentric and radial velocity transformations
- Continuum normalisation
- Order merging



Échelle spectrum from FIES at the Nordic Optical Telescope, La Palma

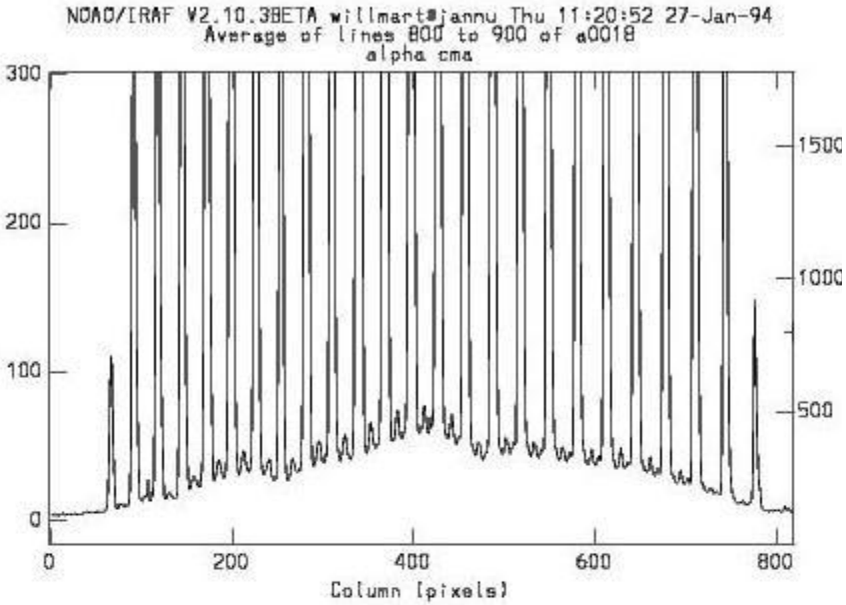
Cut across the orders

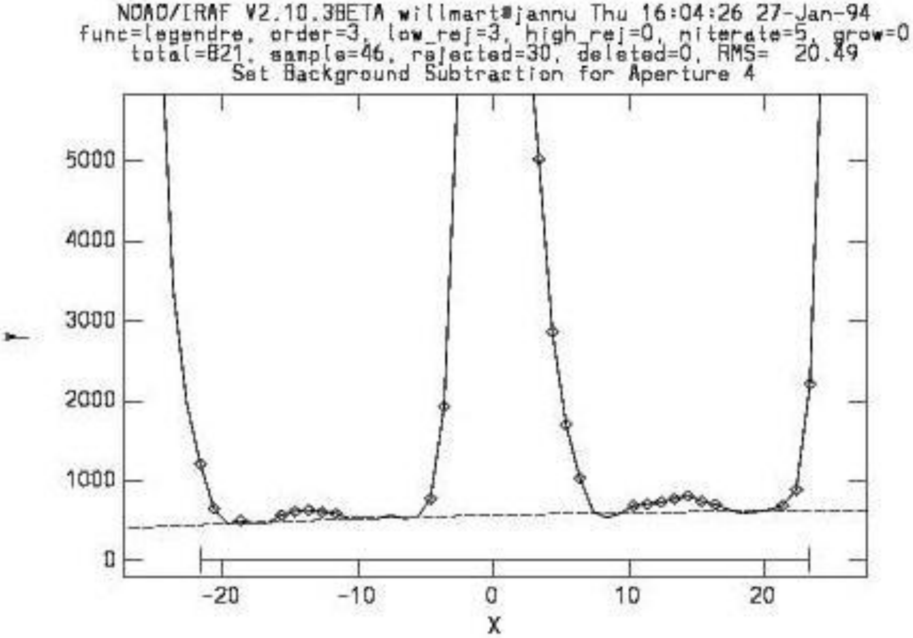


Scattered light 1

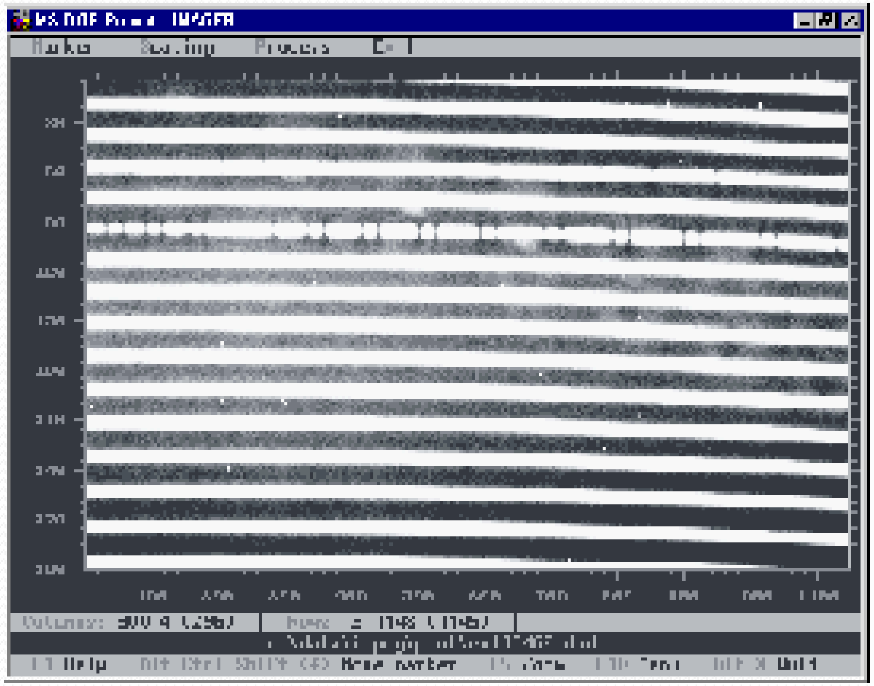
- The background signal in an échelle image consists of:
    - General scattered light
    - Diffuse light in the inter-order space from adjacent orders
    - Sky background
- There are two approaches to determining the background signal level in an échelle image (three if you include not bothering with any background subtraction)
    - use the sky pixels
    - use a surface fitted to the inter-order background over the whole image

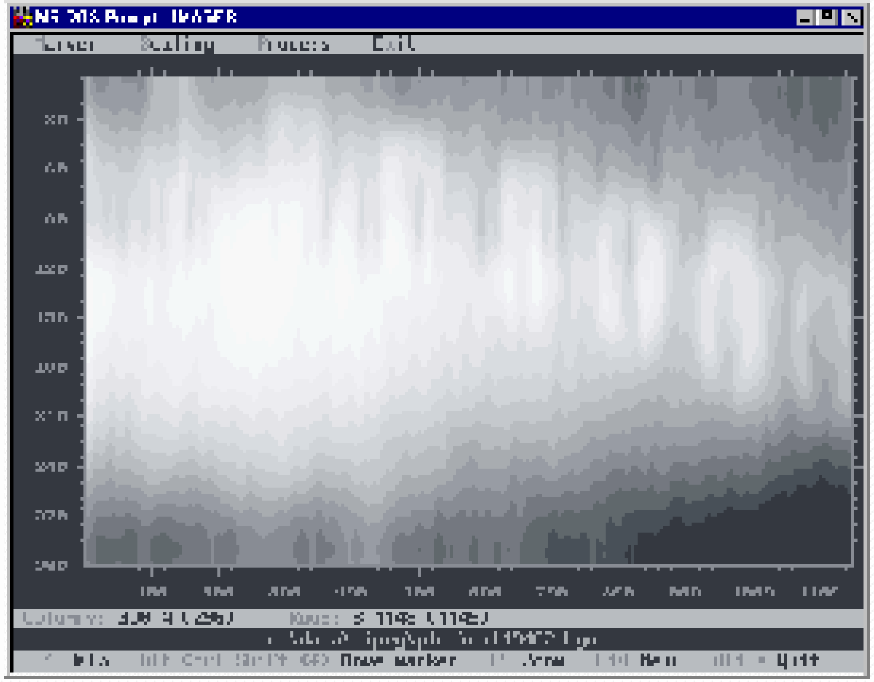
Scattered light 2



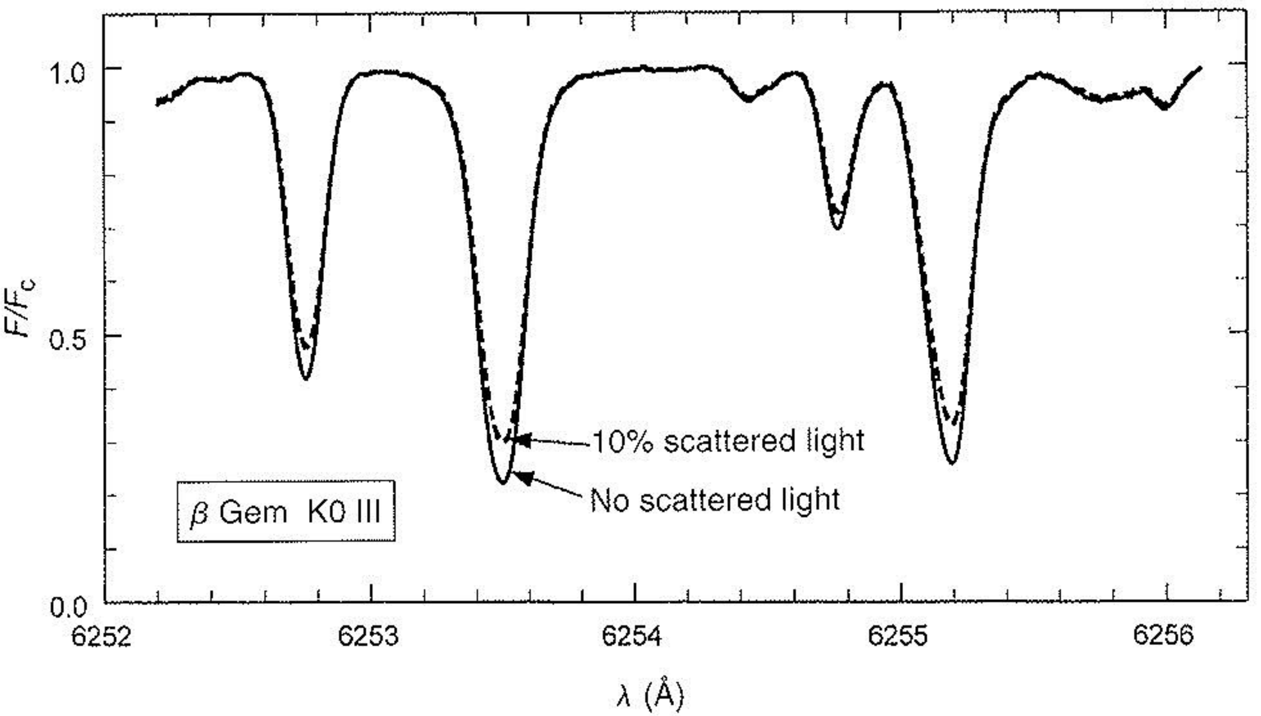


Scattered light 3



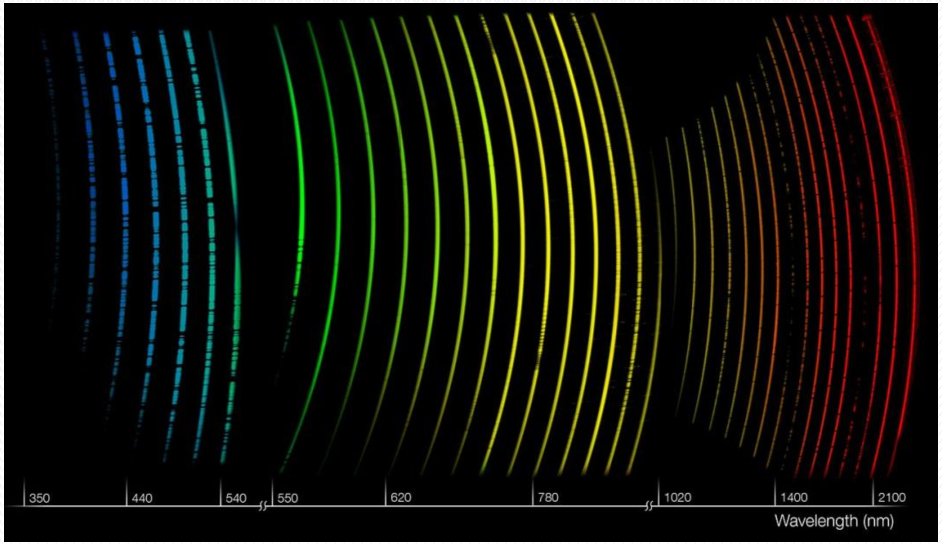


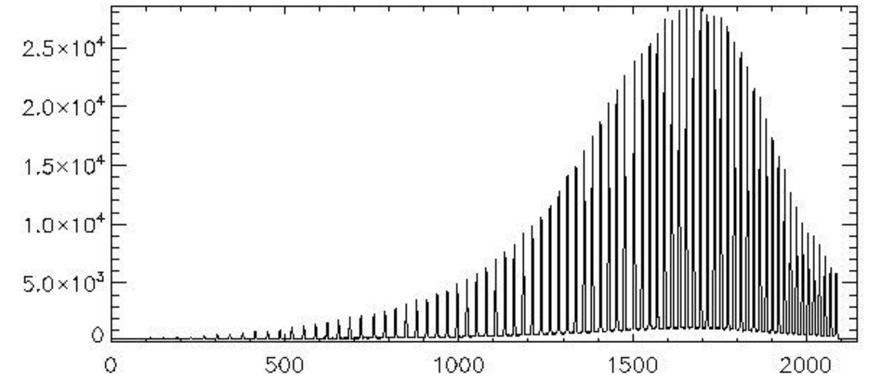
Scattered light 4



Échelle orders

- The spectral orders in échelle are tilted and curved with respect to the regular grid of CCD pixels
- The order definition involves recognition of the spectral orders in the image and approximation of the order position with a bivariate polynomial
- Often ‘order definition frames’, e.g., using a flat field lamp are used.



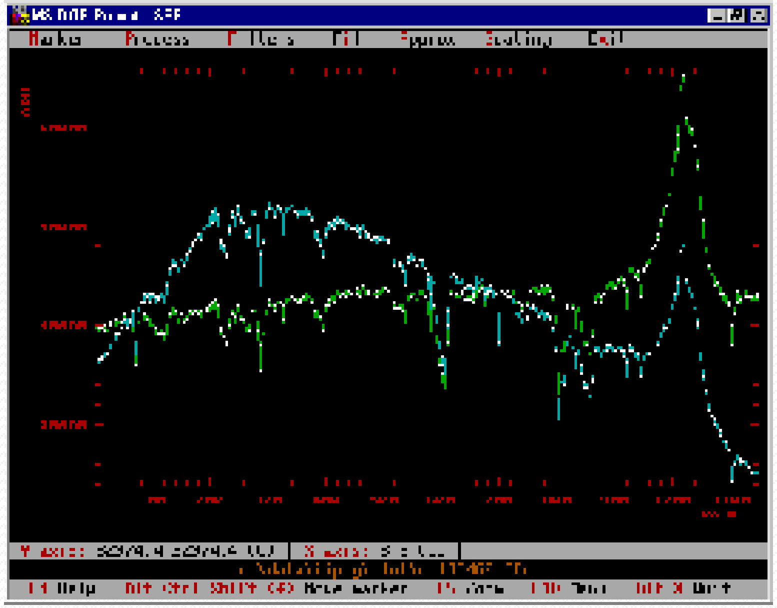


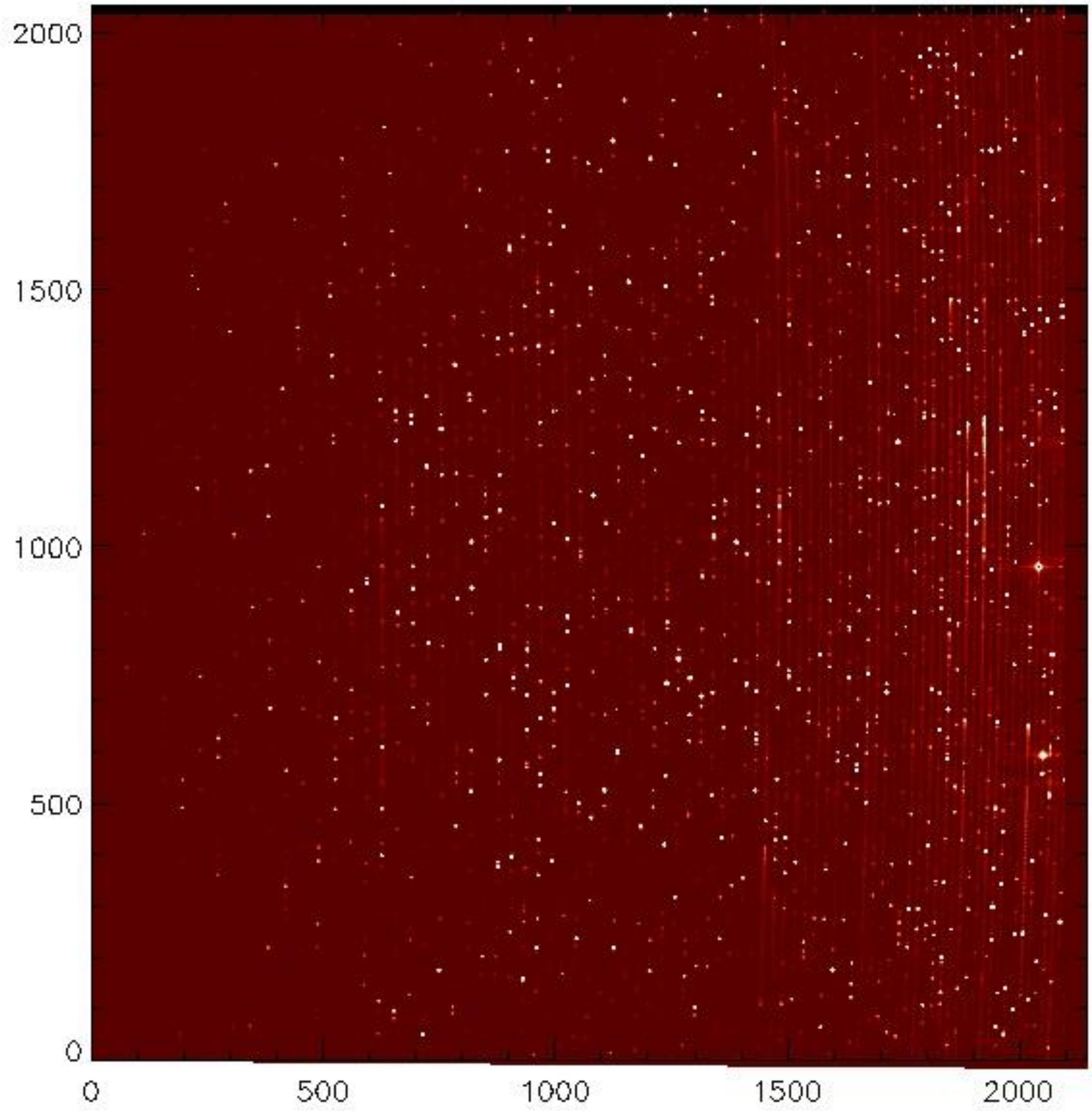
Extraction of the orders

- Usually the spectral orders are integrated at each wavelength pixel by using weighted fit of the spatial profile to the intensity distribution of the pixels across the dispersion
- The spatial profile is obtained by smoothing the normalised intensities along the CCD columns in the dispersion direction
- Since this is a linear fit it allows to distinguish and remove the cosmic ray events at the same time

1D spectra

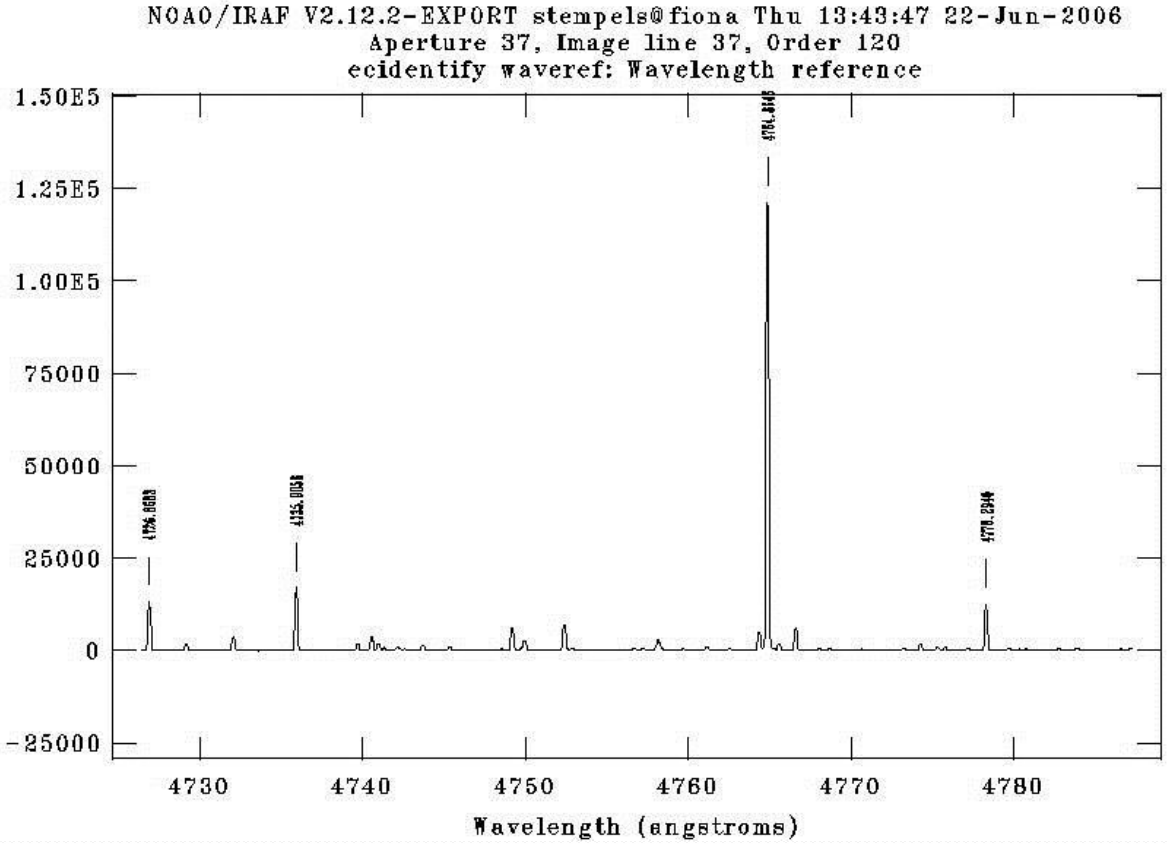
- The integrated 1D spectral orders are usually curved due to the difference in illumination levels in the centre of the focal plane and at the edges
- This can be corrected by using the flat field





ThAr comparison spectrum, FIES

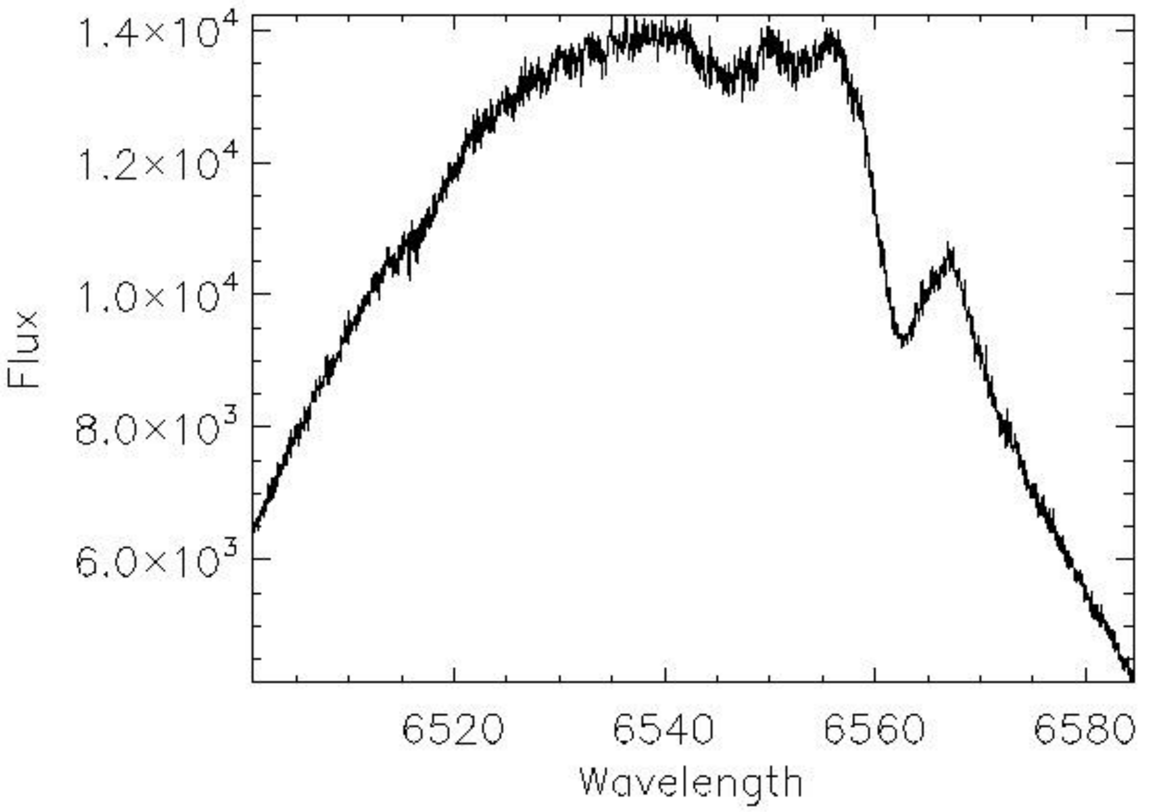
One ThAr order



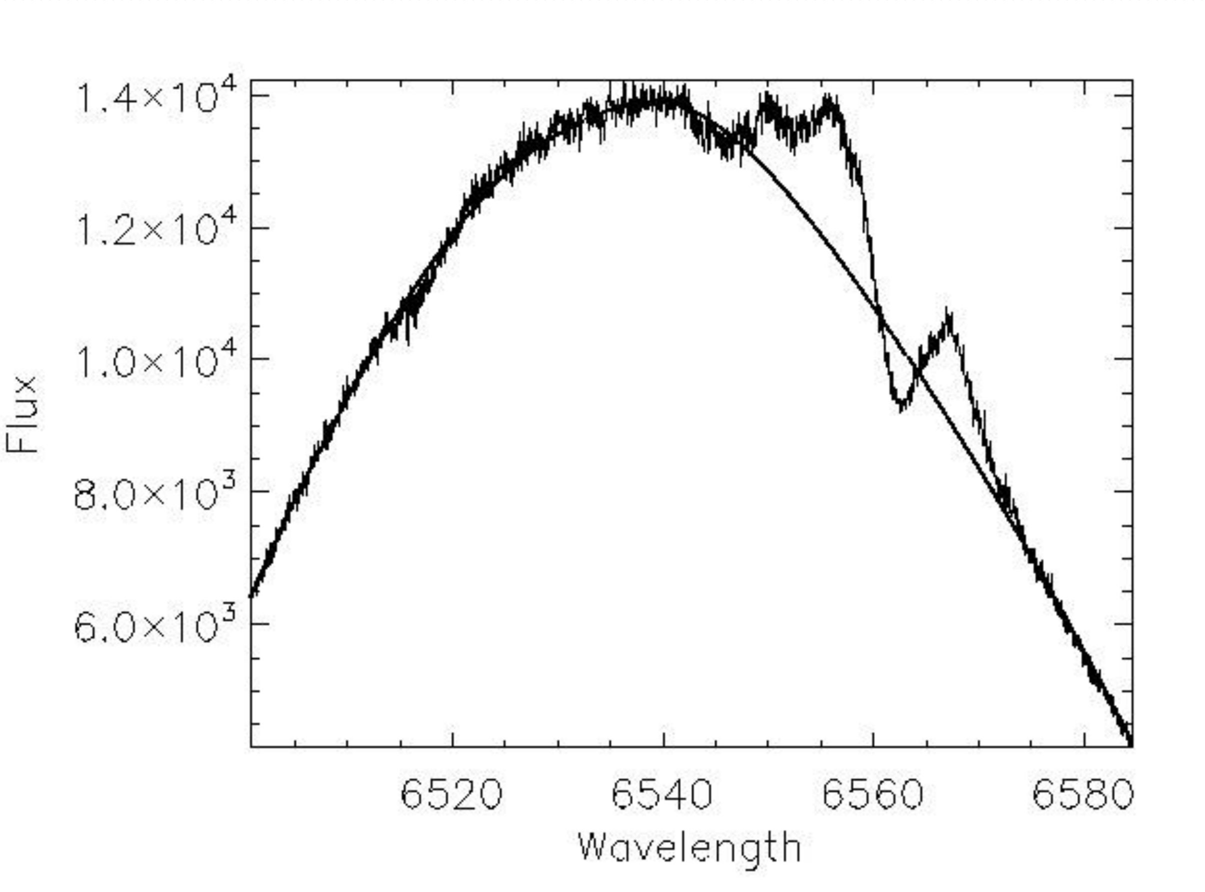
Wavelength calibration

- Obtained ThAr image is reduced: bias and background removed, orders are taken from science frame (or order definition frame)
- From the extracted orders lines are identified
- Hundreds of lines over the whole spectral range is used to obtain a good wavelength solution
- In unstable high resolution spectrographs, like the ones on Cassegrain focus, ThAr spectra before and after the science exposure are used to improve the wavelength solution

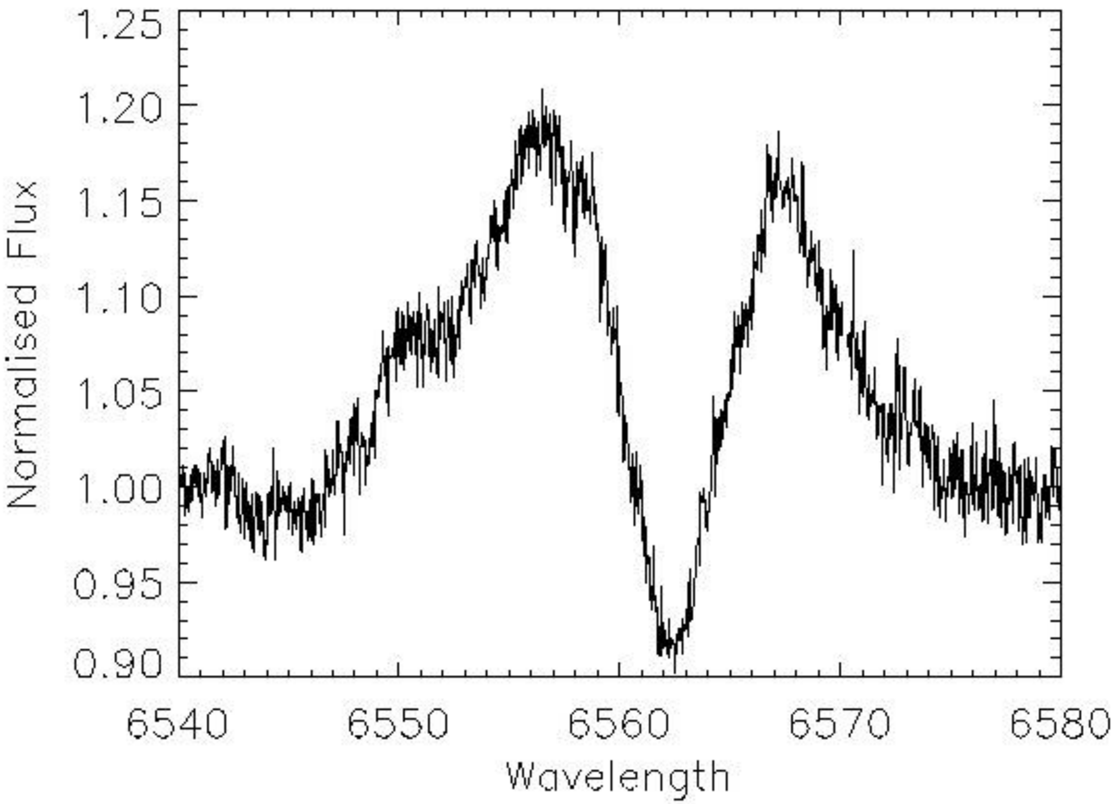
Continuum normalisation



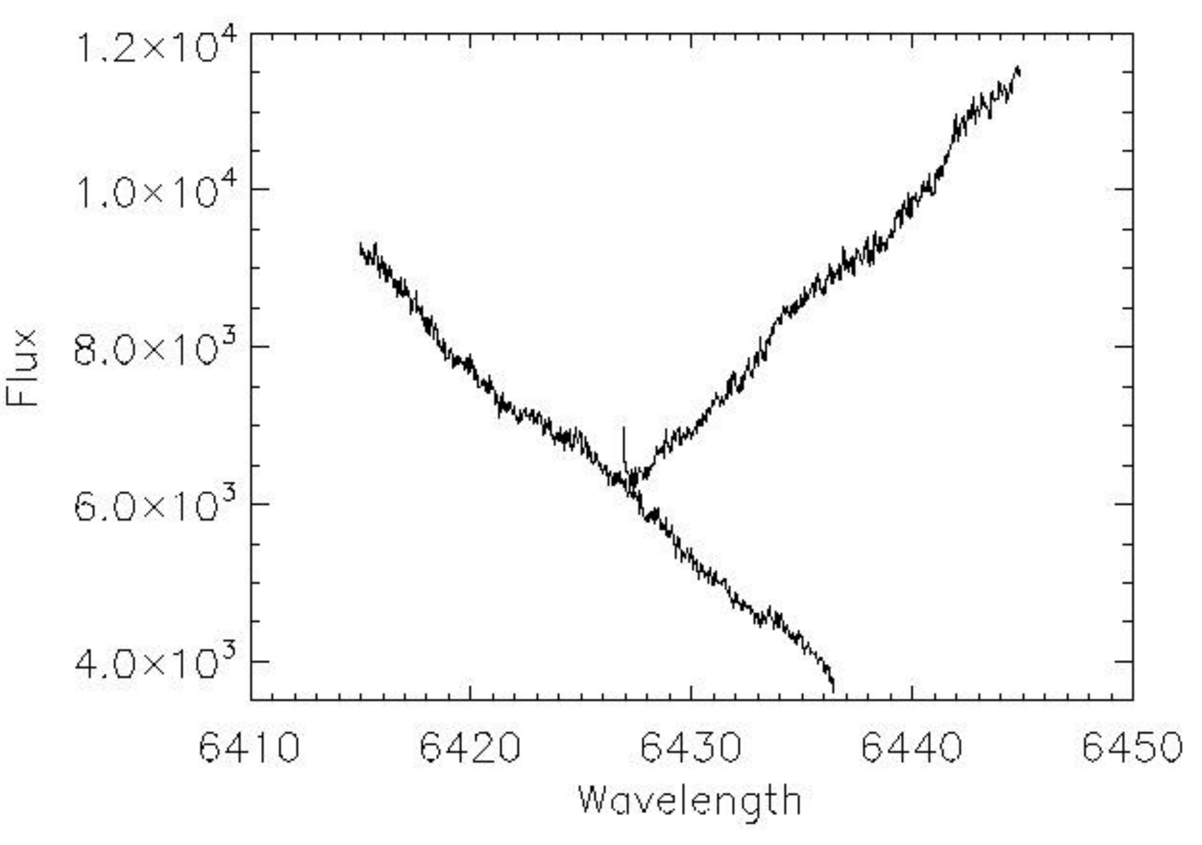
Continuum normalisation

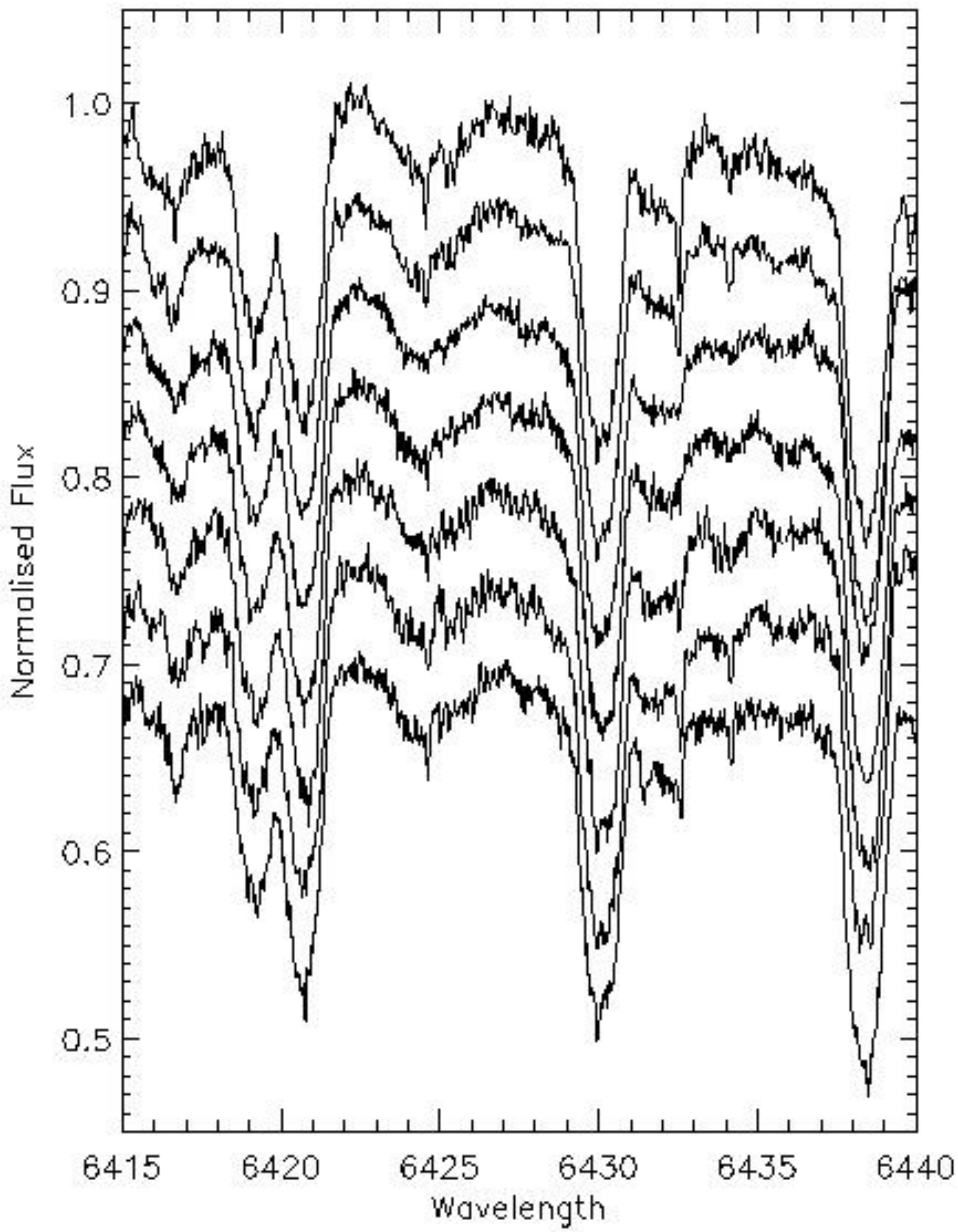


Continuum normalisation



Merging orders



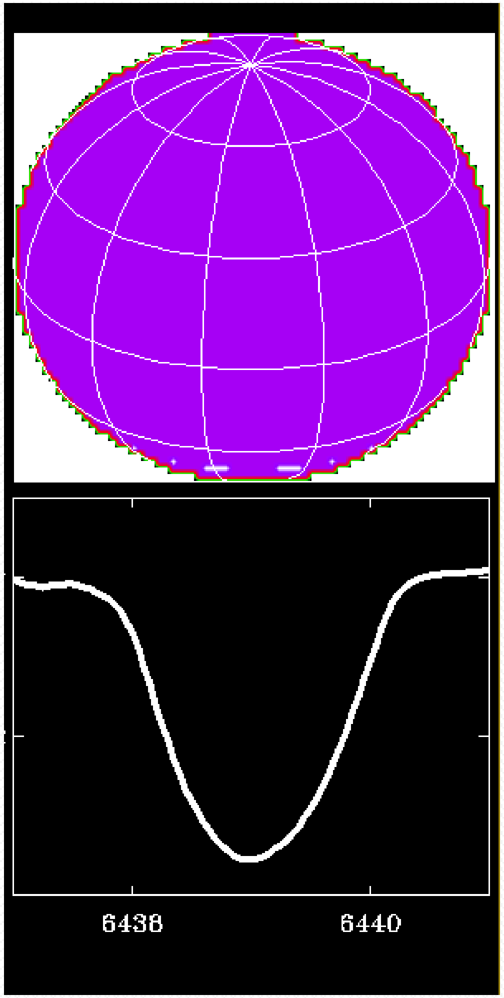


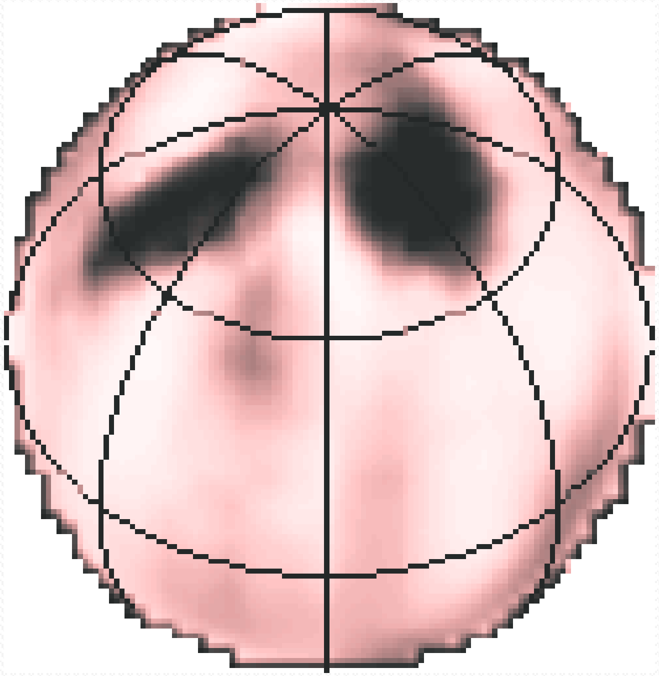
Atmospheric absorption lines with high spectral resolution

Standard stars

- In high resolution spectroscopy you are usually interested in line profiles, which means that you do continuum correction
- Thus you are often not interested in spectrophotometric standards
- But you might want to have a hot star to help removing the atmospheric absorption lines
- And if you are interested in precise radial velocities, you would also like to have a radial velocity standard

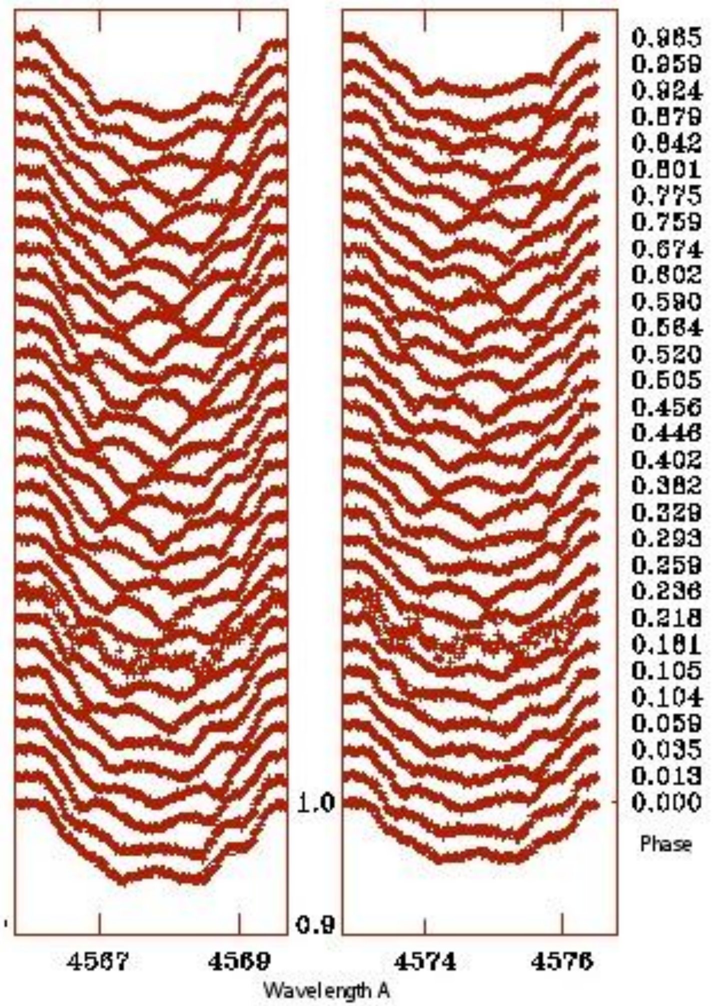
Some science with high spectral resolution, **Doppler imaging**





II Peg by Berdyugina et al. 1998

Some science with high spectral resolution, **Pulsations**

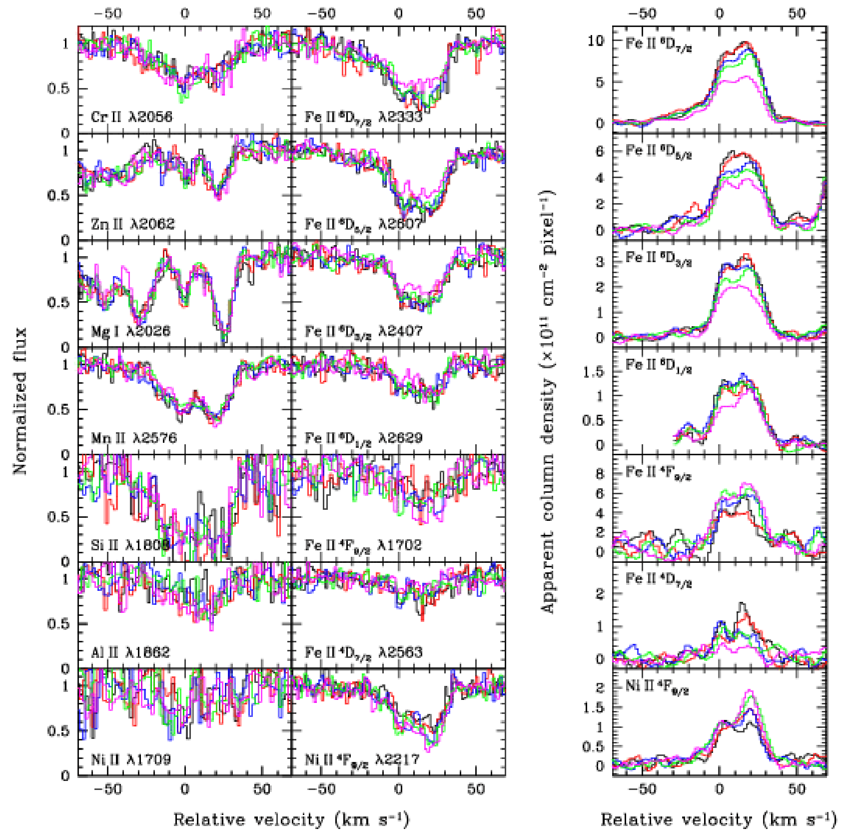


- β Cephei star ω¹ Sco
- R=65000
- line-profile variations in the Si III triplet
- Pulsation frequency of 15.0 cycles/day
- pulsational degree l=9±1.

Telting & Schrijvers1998

Some science with high spectral resolution, **GRB spectroscopy**

- Line variations of GRB spectra
- Spectra 10 to 70 min after the burst trigger
- R ~40 000
- At redshift of 1.4!



Vreeswijk et al. 2007