Spectroscopic Instrumentation

Theodor Pribulla

Astronomical Institute of the Slovak Academy of Sciences,
Tatranská Lomnica, Slovakia

Spectroscopic workshop, February 6-10, 2017, PřF MU, Brno

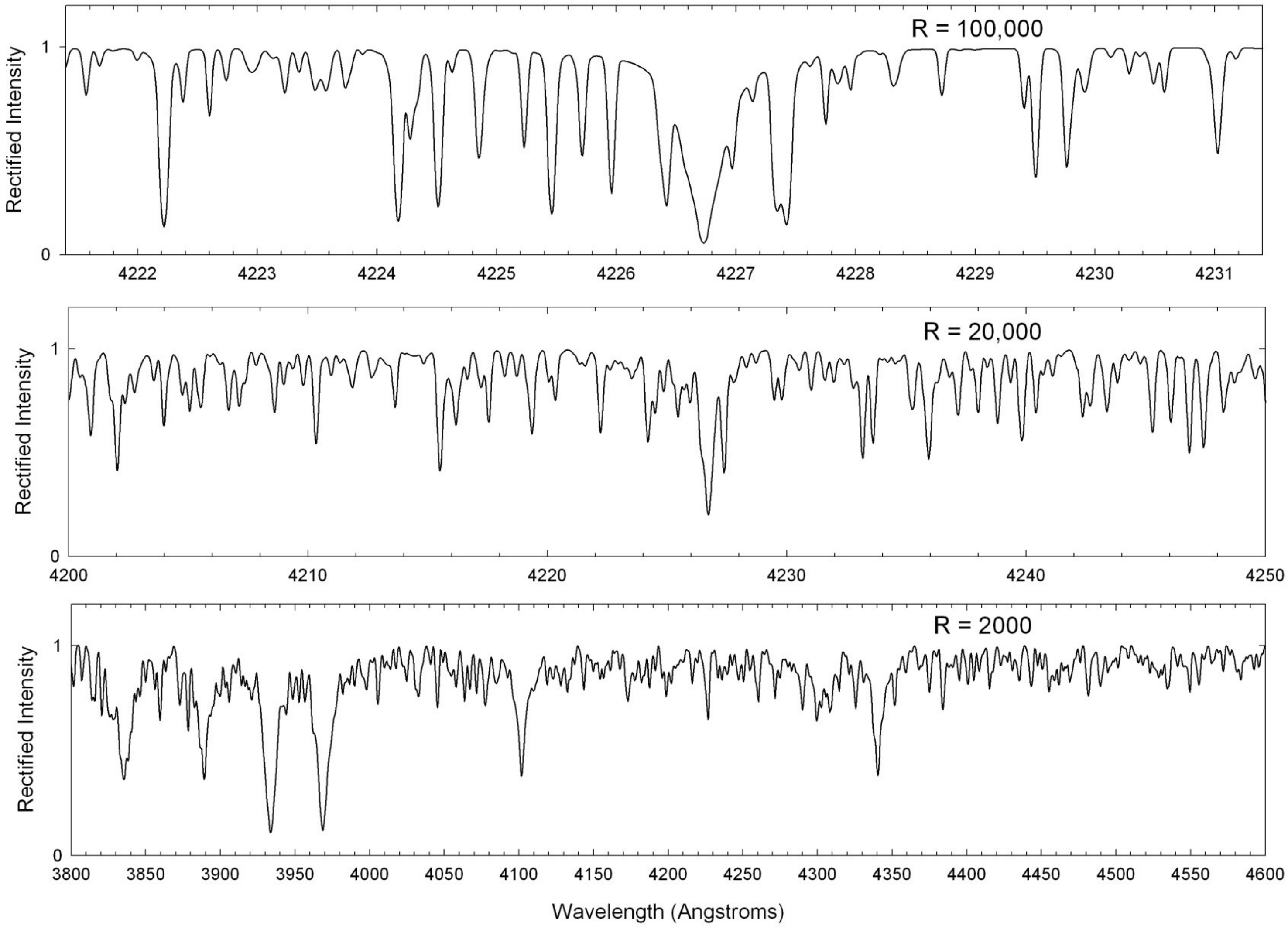
Principal parameters of a spectrograph

- spectral resolution $R = \lambda/\Delta\lambda$ (FWHM)
- optical efficiency=throughput - every photon counts !!!
- useful wavelength range
- RV/wavelength stability
- amount of scattered light

Dispersion:

- $10 < R = \lambda/\Delta\lambda < 1000$ (low)
- $1000 < R < 10000$ (medium)
- > 10000 (high)

Spectral range vs. resolution



Spectrograph types

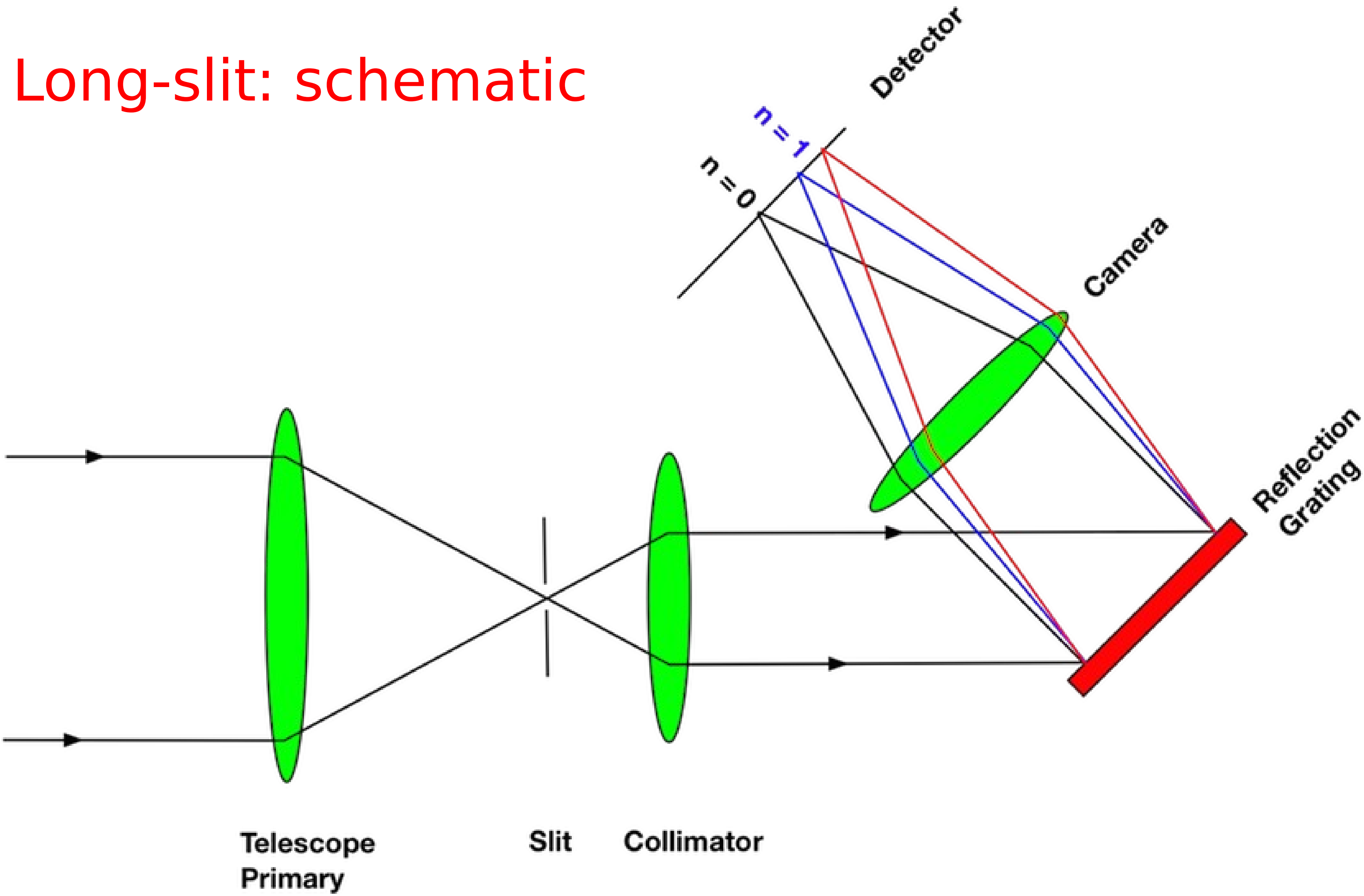
Design

- objective prism, fiber-fed, slit-mounted (telescope focus), coudé (=elbow)
- long-slit, échelle, multi-object/fiber, Fourier transform
- single-channel, double channel (typically red and blue channel)

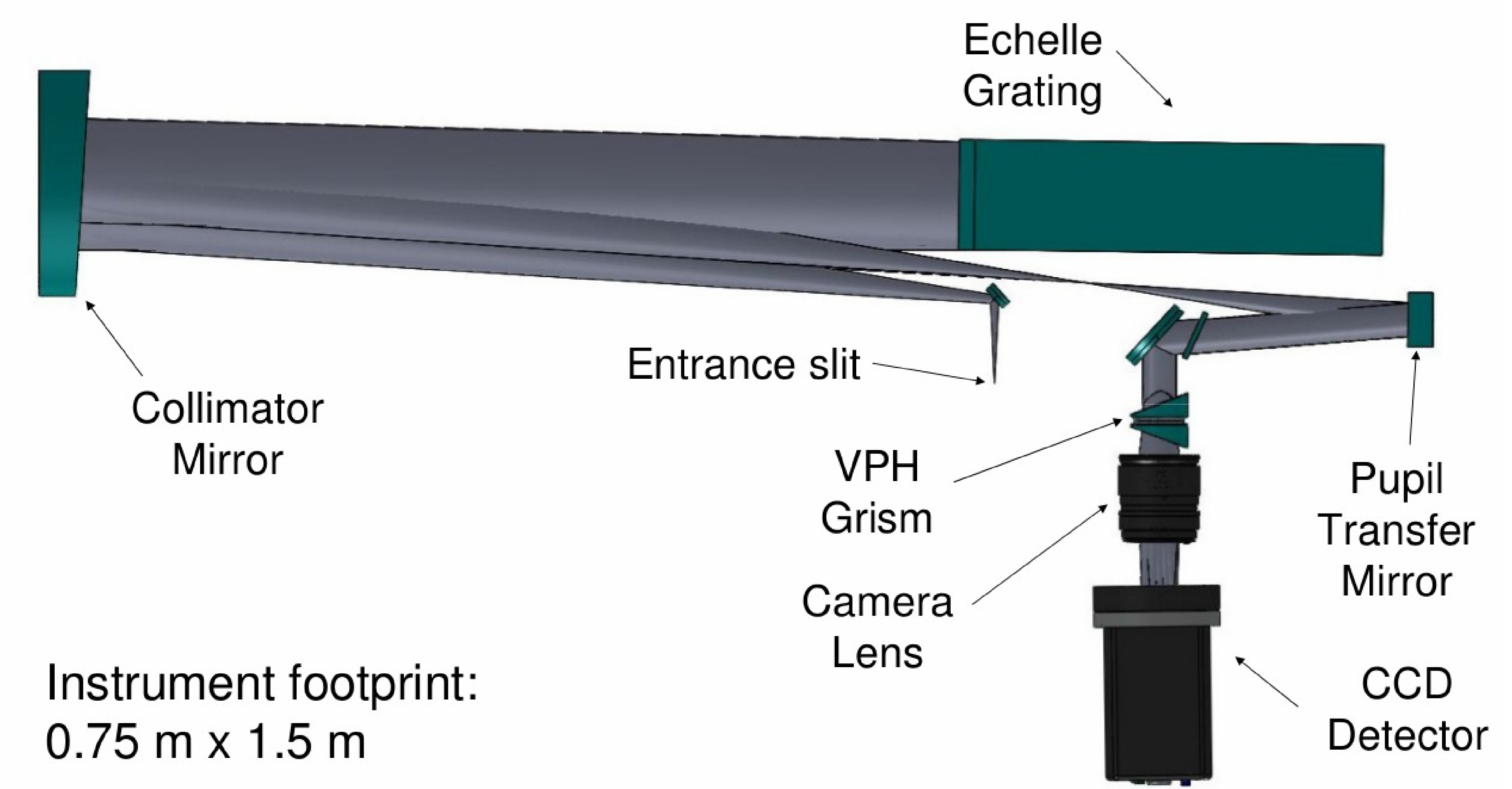
Spectroscopy facts

- the larger telescope the larger spectrograph
- the larger seeing the larger spectrograph
- the large resolution the smaller SNR

Long-slit: schematic

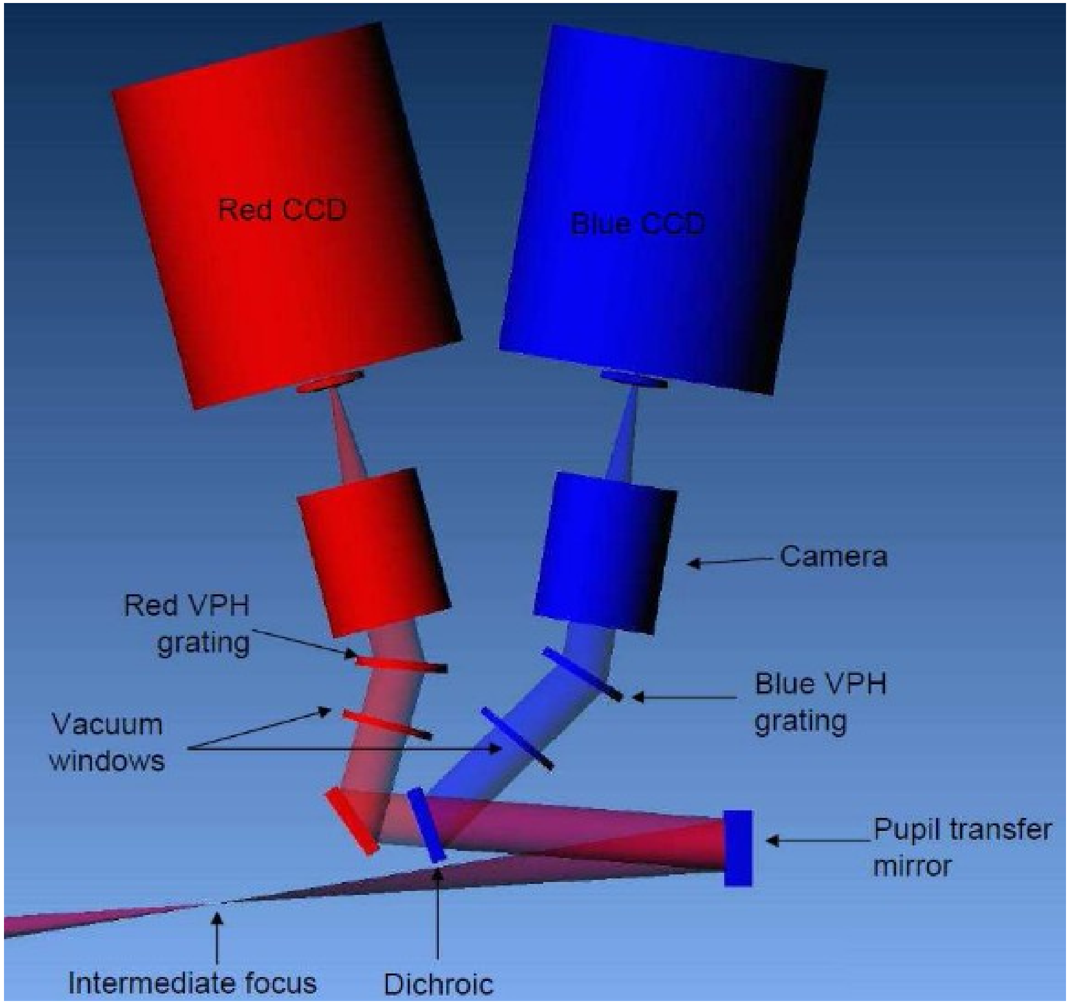


échelle white-pupil design: more realistic...



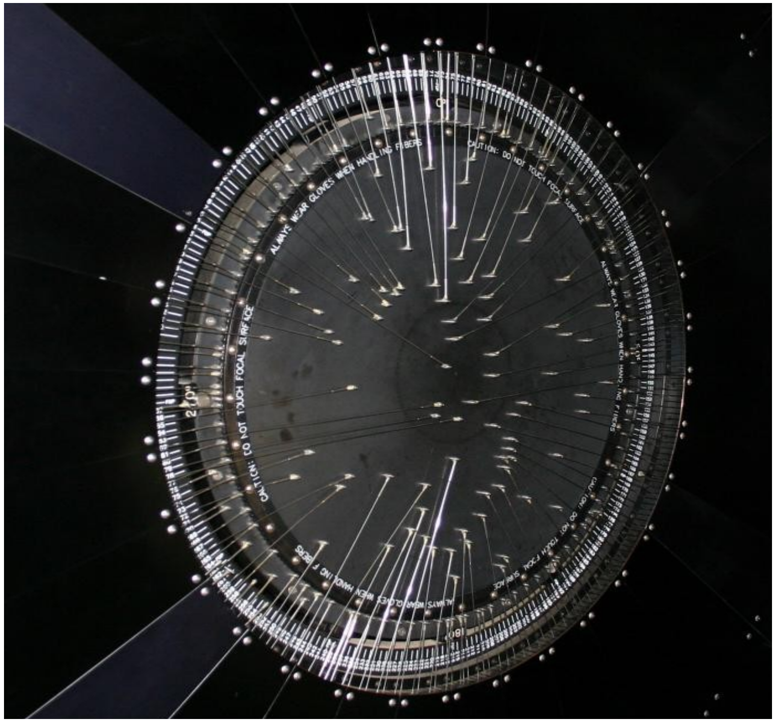
* Littrow configuration: angle of incidence equals to angle of diffraction

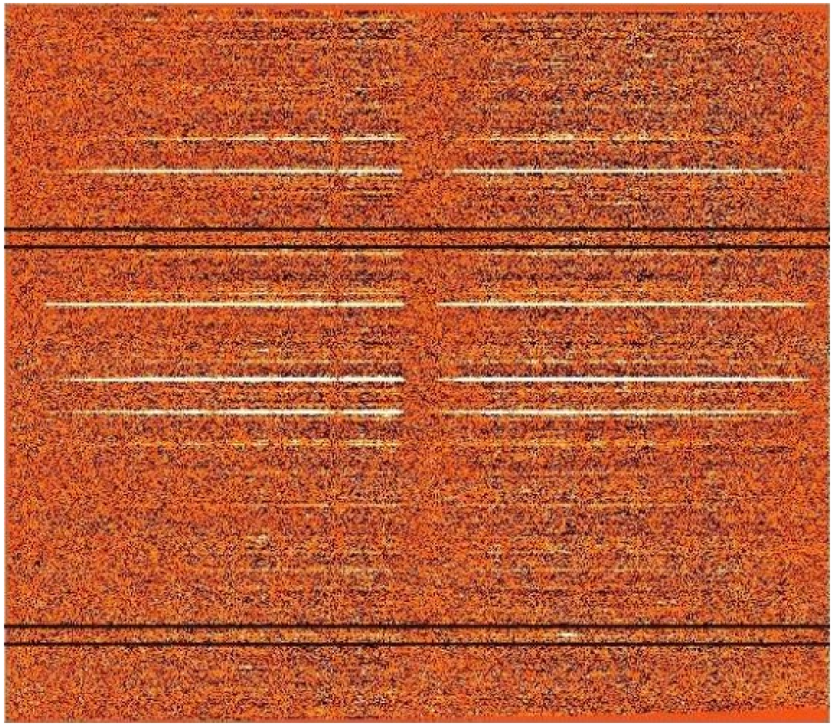
échelle white-pupil design: two channels

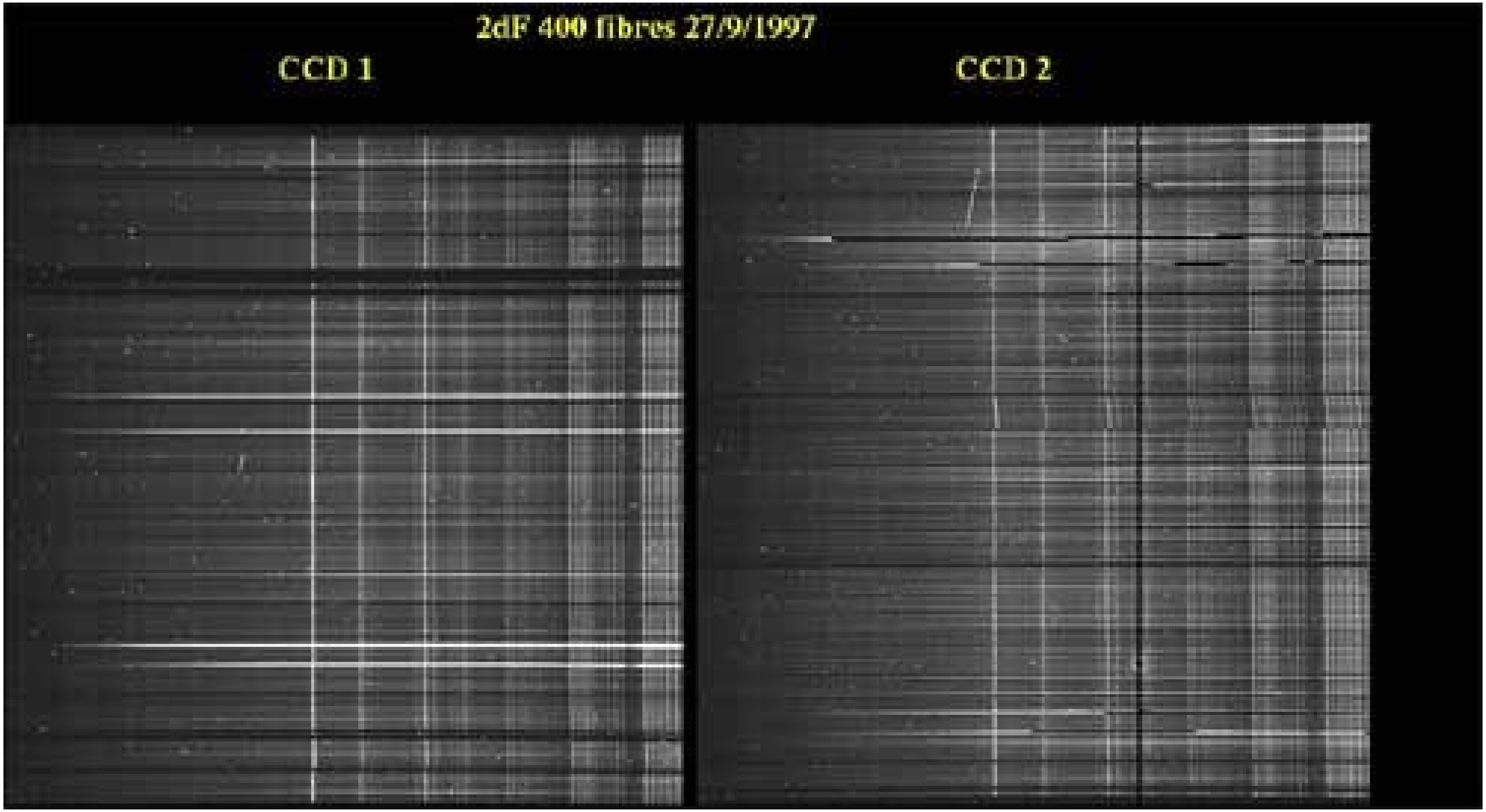


Multi-object spectrographs

- Observing one star at a time is inefficient
- ideal for stellar clusters
- typically a number of optical fibers put at locations of stars
- fiber positioners or masks, up to several hundred fibers

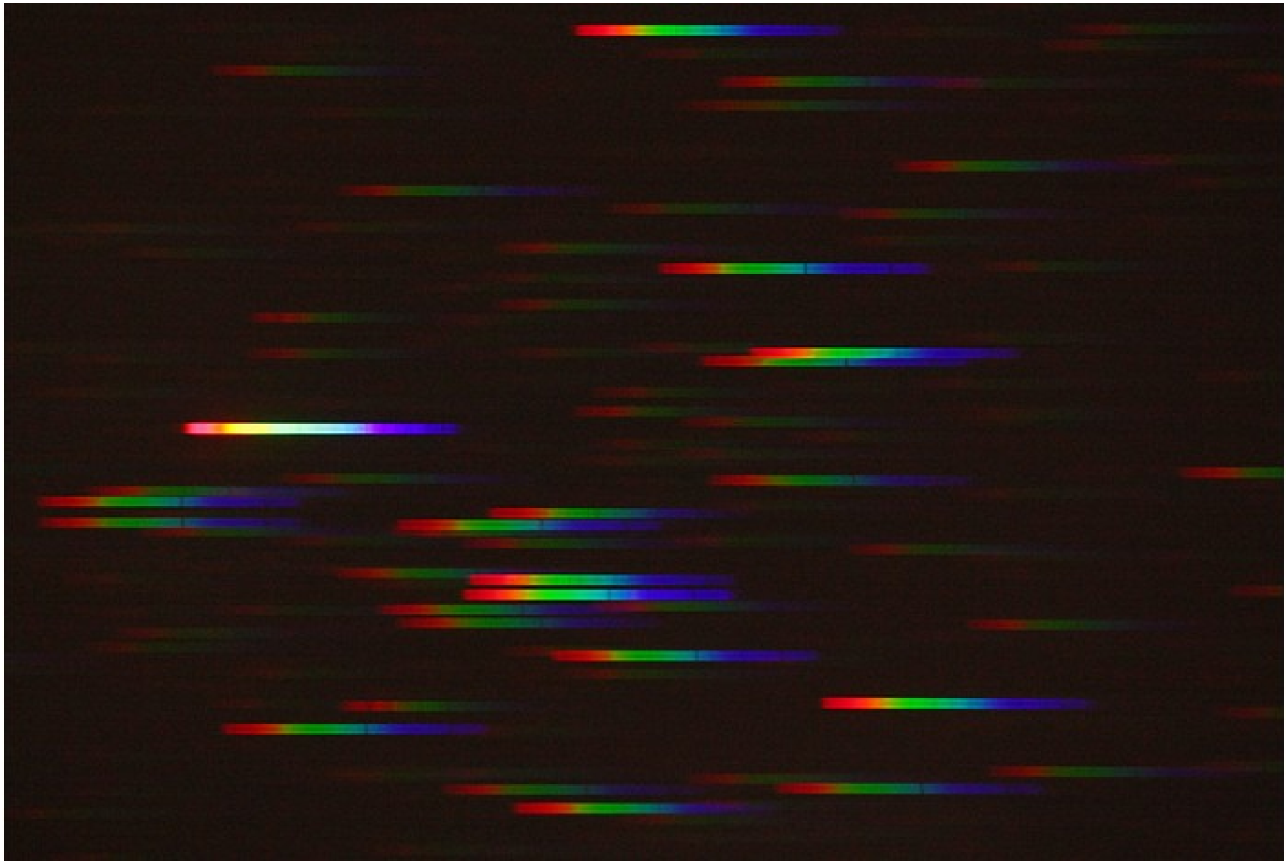


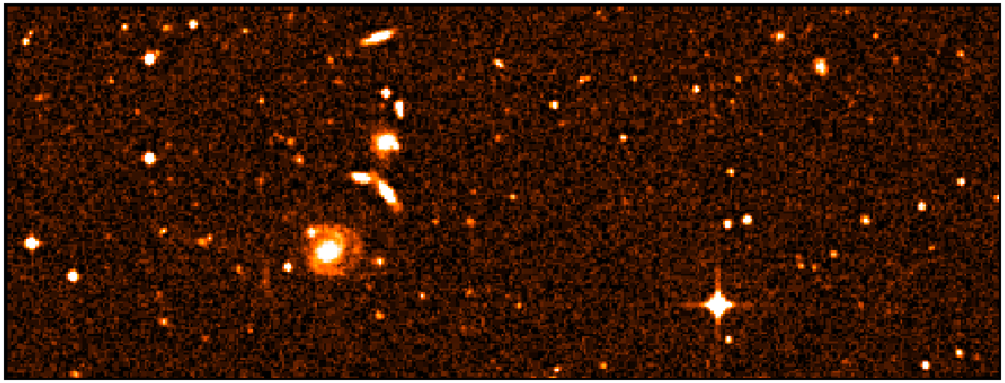


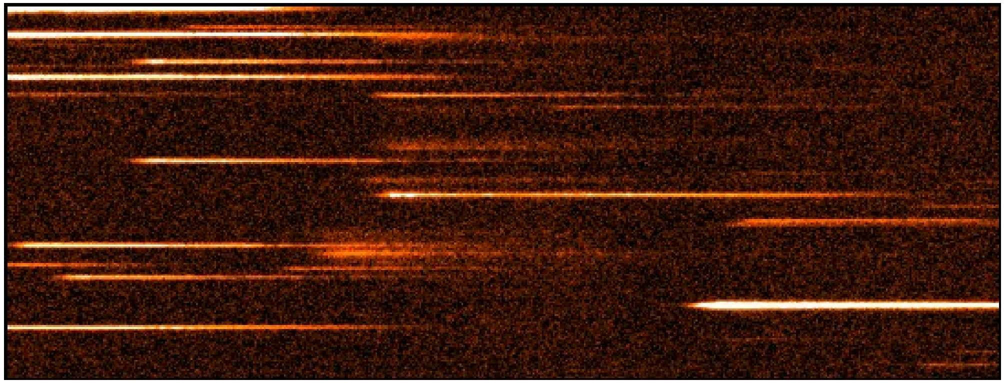

2dF 400 fibres 27/9/1997
CCD 1
CCD 2

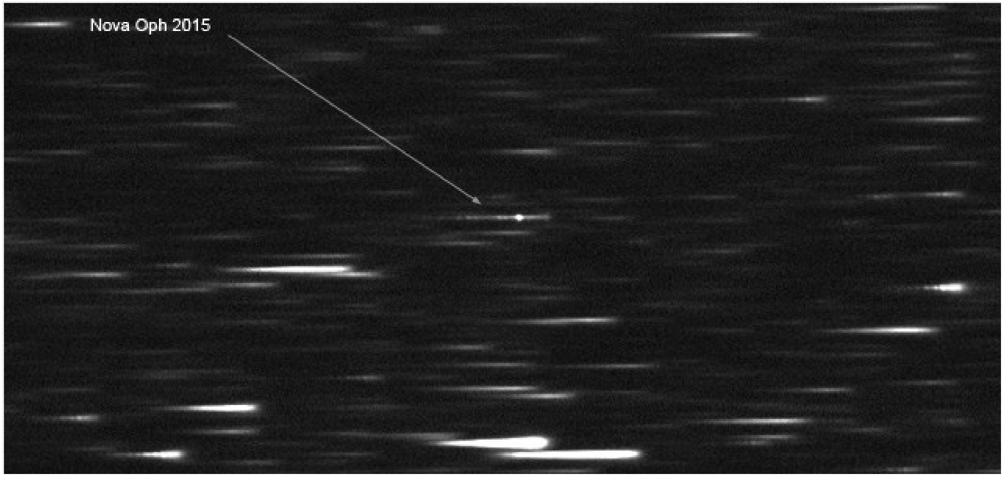
Objective prism spectroscopy

- a wedge prism is mounted at the top of the telescope (before the aperture)
- for a 60cm telescope typically 10-degree wedge
- Ideal for surveys as low-dispersion multi-object spectrographs
- Principal disadvantage: spectra overlapping





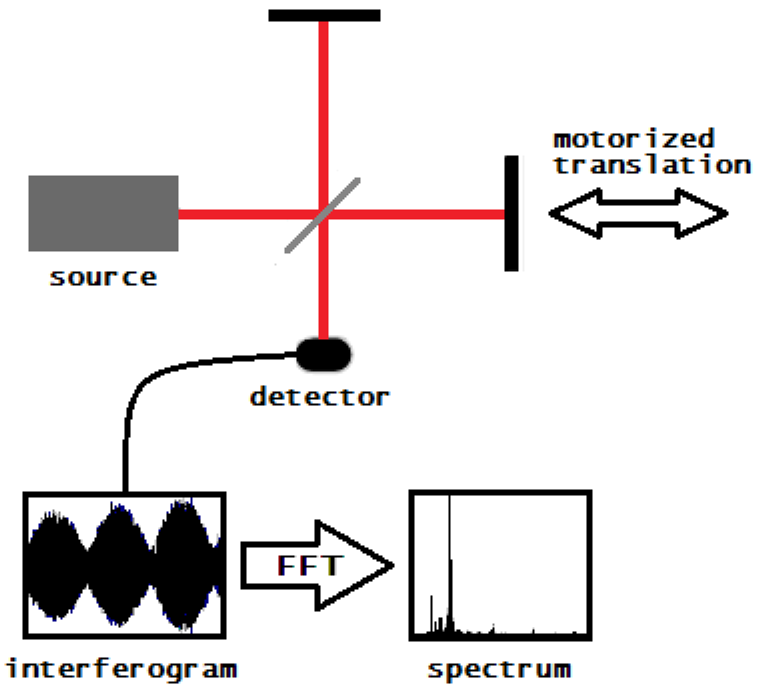


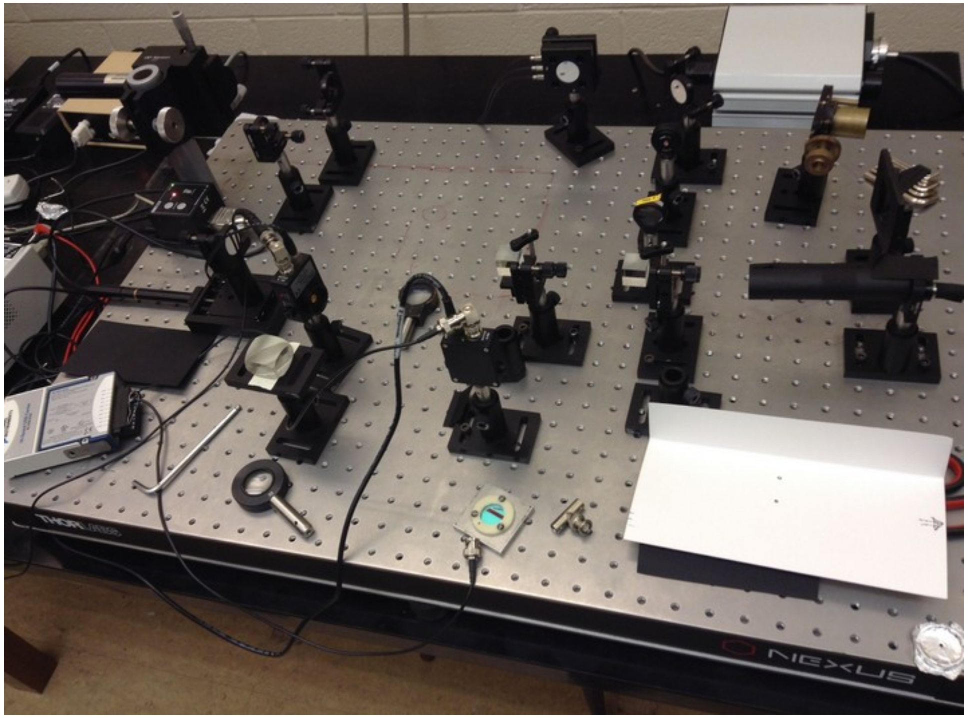


Prism of the Rozhen 50/70
Schmidt telescope

Fourier-transform spectrographs

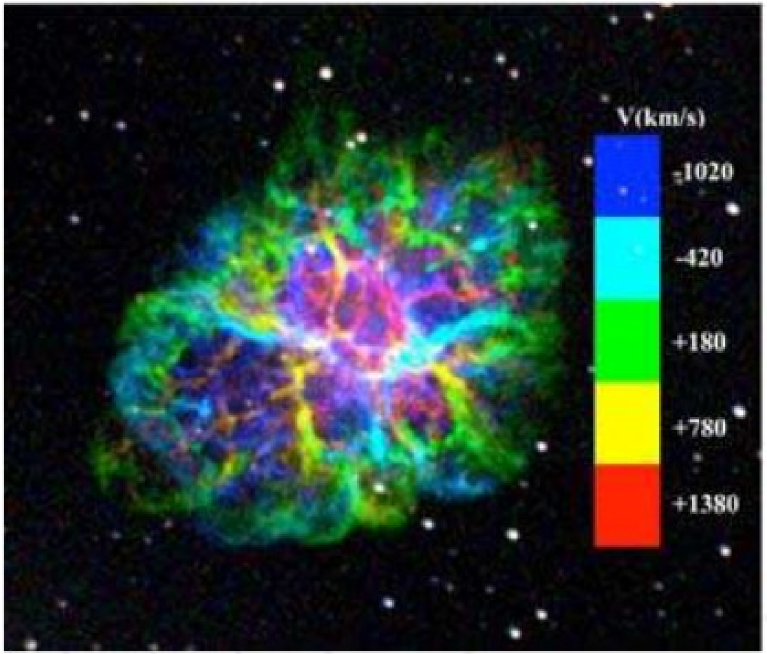
- Fourier transform spectrometer is based on a Michelson interferometer
- Intensity as the function of the movable mirror is recorded, spectrum is obtained as the Fourier transform
- FTS were originally introduced in the infrared domain, where only single-element detectors were available

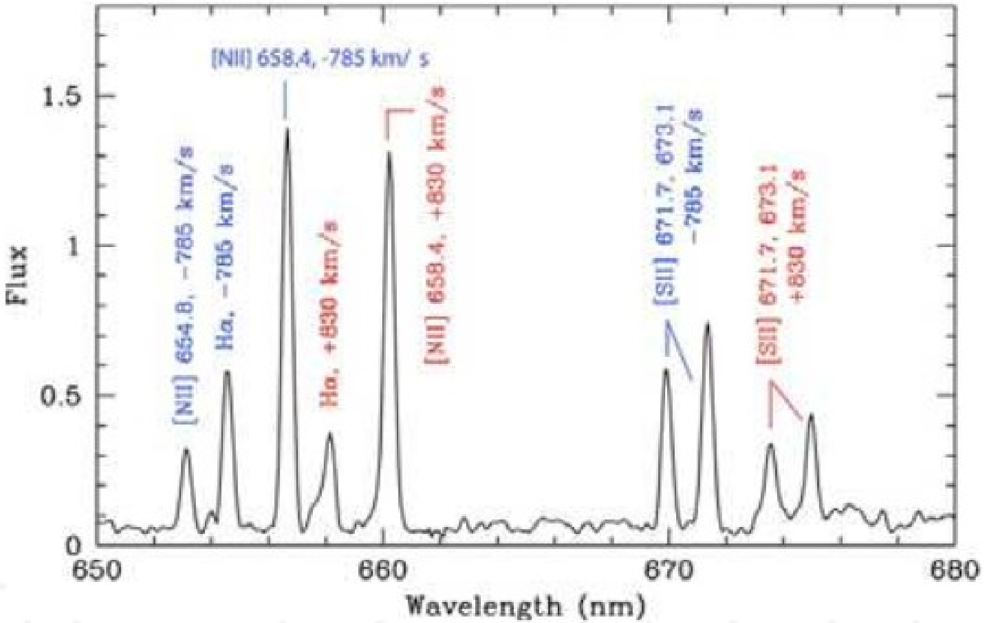




Fourier-transform spectrographs

- FTS reach very high spectral resolutions R > 100000
- very wide wavelength range typically far to IR depending on the detectors (diode is enough)
- Principal disadvantages: one scan lasts several minutes, requires bright sources, requires ultimate instrument stability to vibrations
- Recently imaging FTS = FTIS





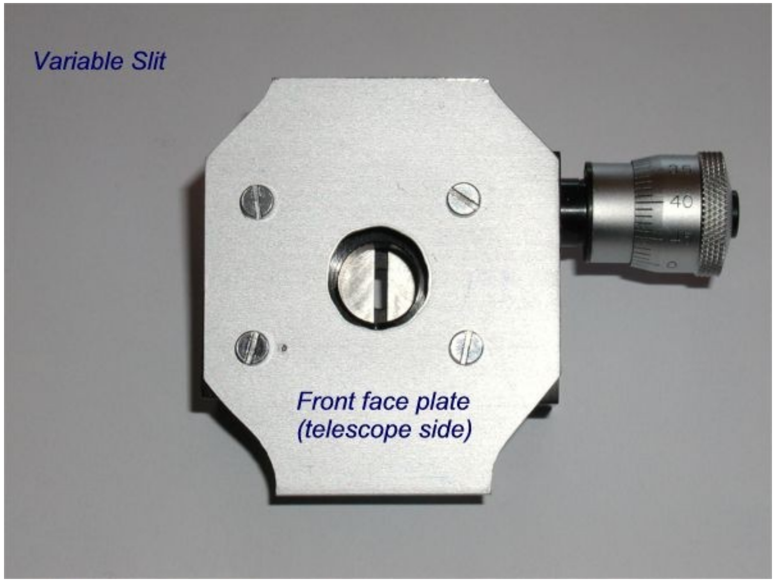
Applications

- objective prism + multi-object spectrographs: surveys, classification
- long-slit spectrographs: spectrophotometry, classification, extended sources
- échelle spectrographs: line profile analysis, abundance analysis, Doppler tomography
- FTS: molecular vibrational and rotational spectra, resolvng fine structures, multiplets

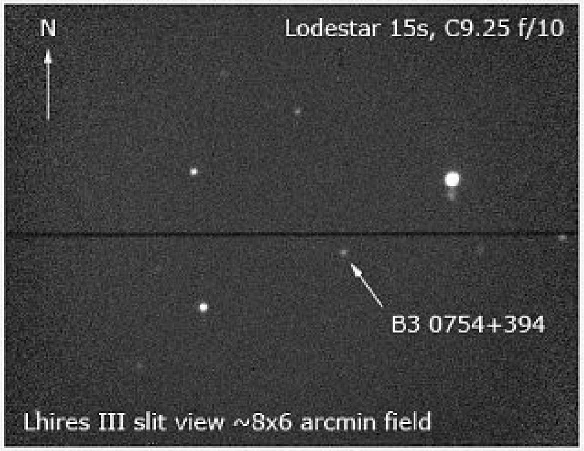
Main components of a spectrograph

1. slit

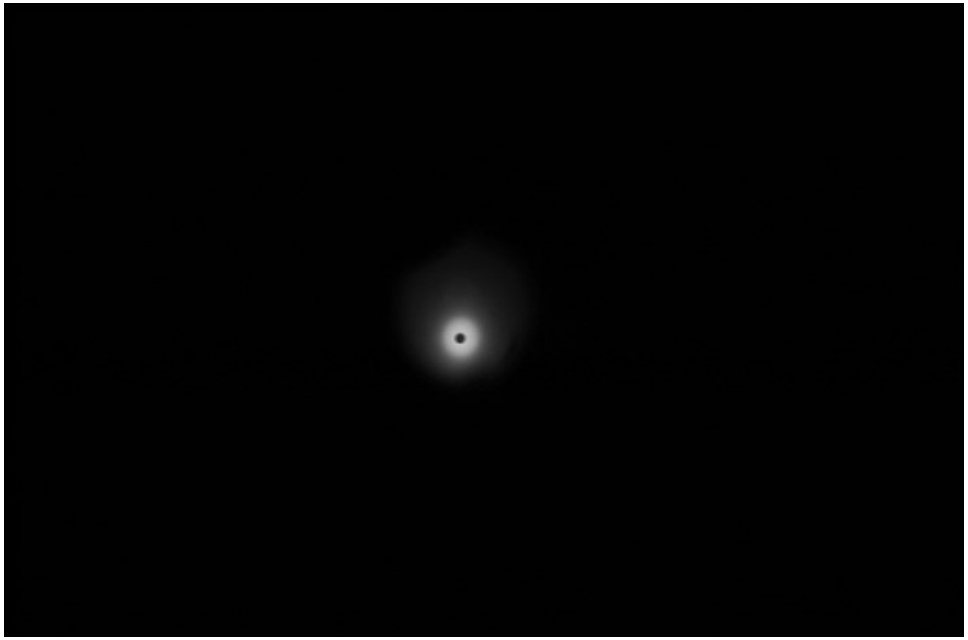
- entrance aperture of the spectrograph
- size of the slit determines spectral resolution
- slit limits light of sky and other nearby sources
- slit sets the reference point for the wavelength system
- recorded spectrum is made of slit images

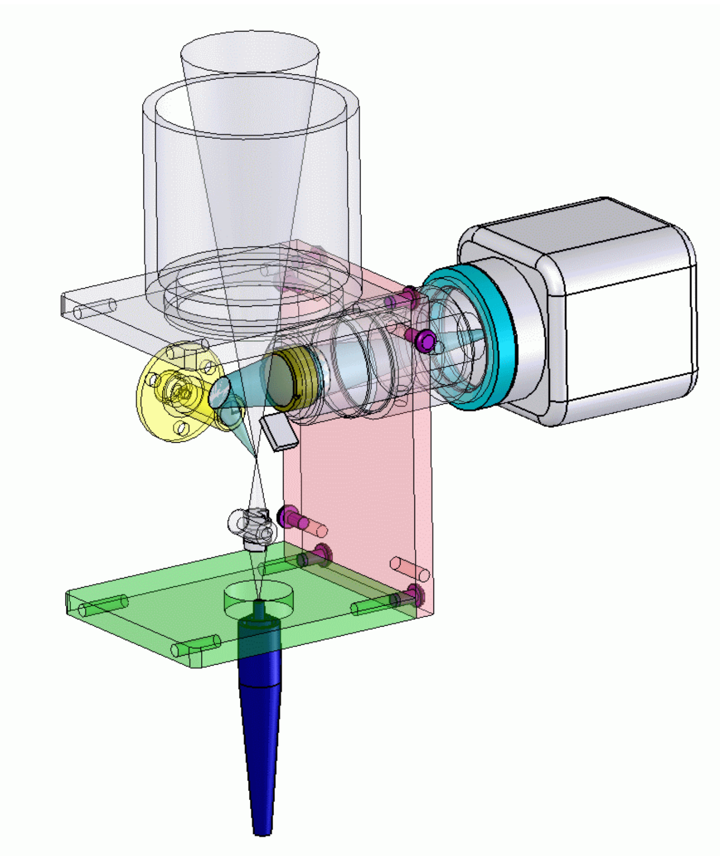


Slit guiding unit



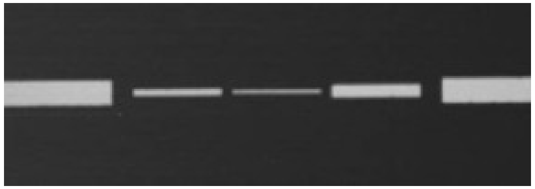
- inclined mirror reflects telescope image to a video or a fast CCD camera
- reflective and inclined slit for guiding
- exposure-meter (behind the slit), few % of light is taken to check the signal

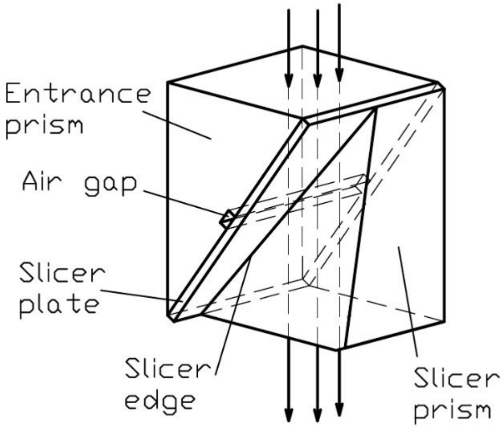


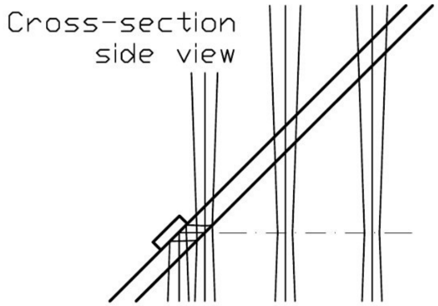


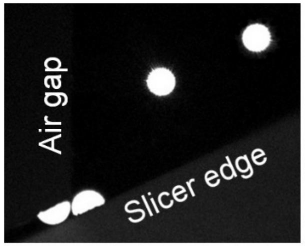
Slits & aperture plates

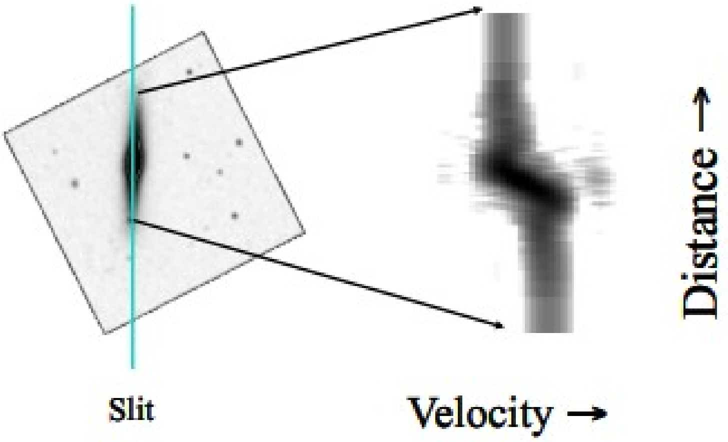
- slit must match the typical seeing disc at the telescope focus: the slit reduces amount of incident light: slit losses
- aperture plates/ deckers: enable selection of various slits (shapes/sizes)
- for échelle limited by inter-order overlap
- image slicers to save on big gratings and optics
- long-slit spectroscopy







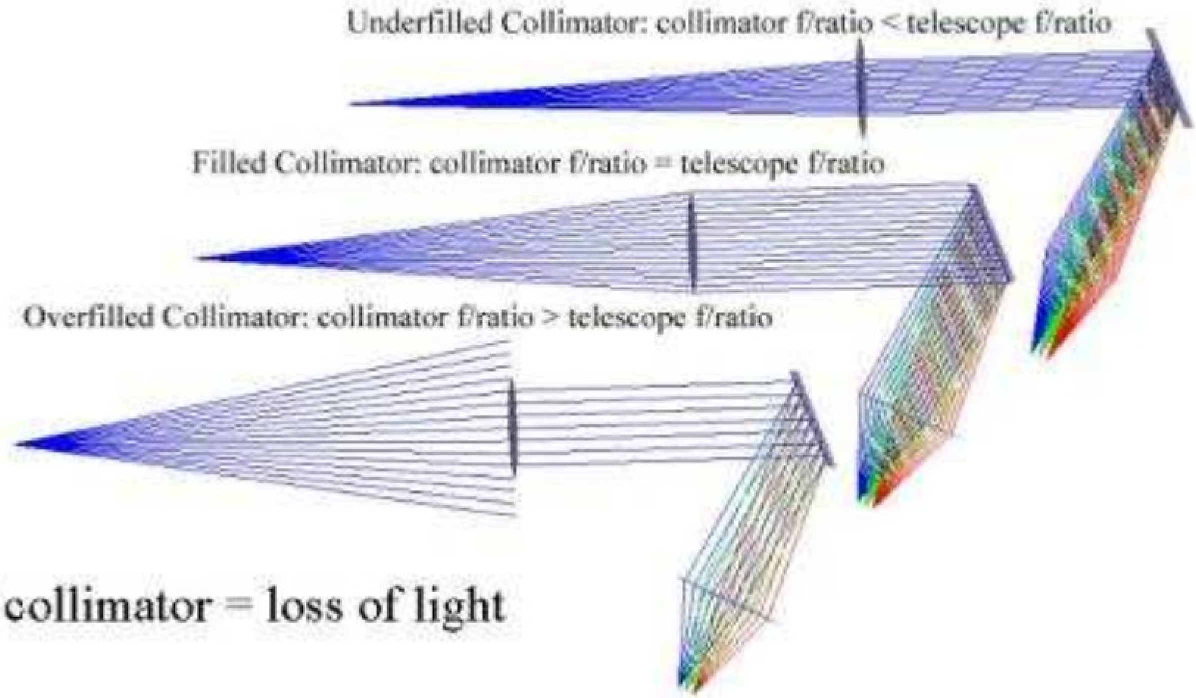




2. collimator

- collimator makes the divergent beam to be parallel
- focal ratio of collimator must match focal ratio of the telescope
- the collimator size determines the size of the grating, it scales with the telescope size to preserve the same resolution
- small spectrographs use an aspheric lens (introduces the chromatic aberration, absorbs UV light...)
- larger spectrographs use on-axis or better off-axis parabola (no vignetting)

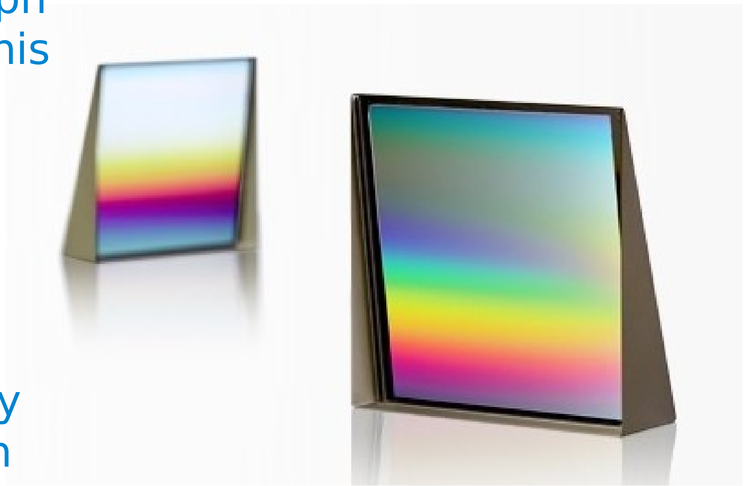
- Underfilled collimator = loss of resolution

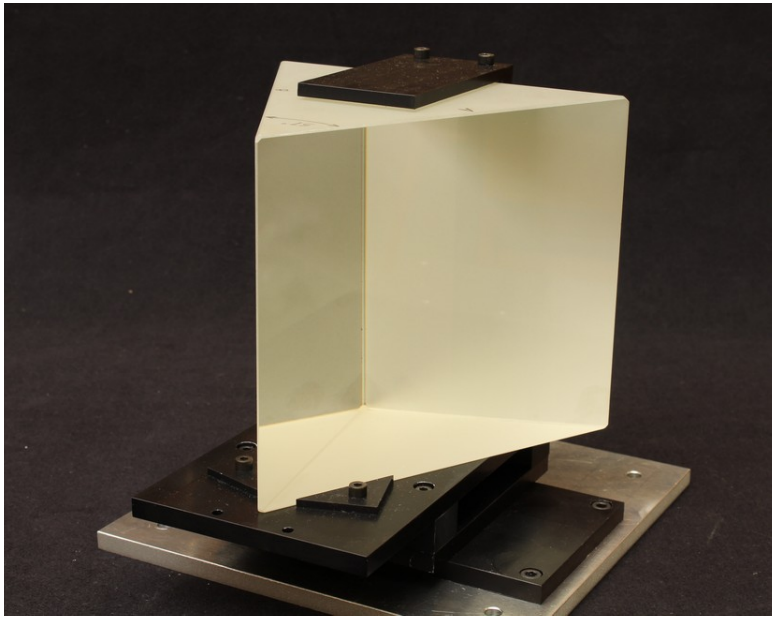


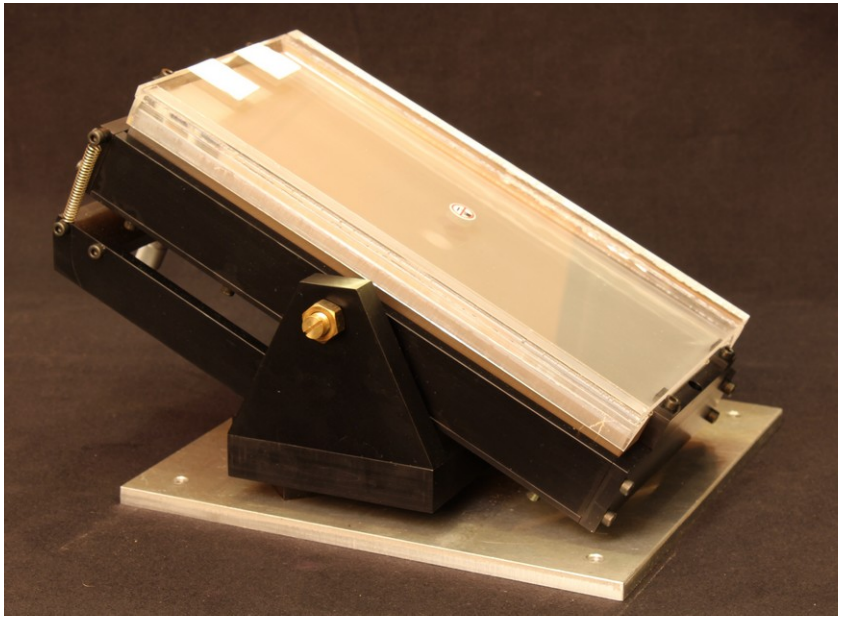
- Overfilled collimator = loss of light

3. dispersion element

- without the dispersion element the spectrograph re-images the slit on the CCD, with disperser this is still valid for monochromatic light
- glass prism
- ordinary or blazed grating
- échelle grating
- grism = grating engraved on a prism = quickly converts imaging instrument to a spectrograph





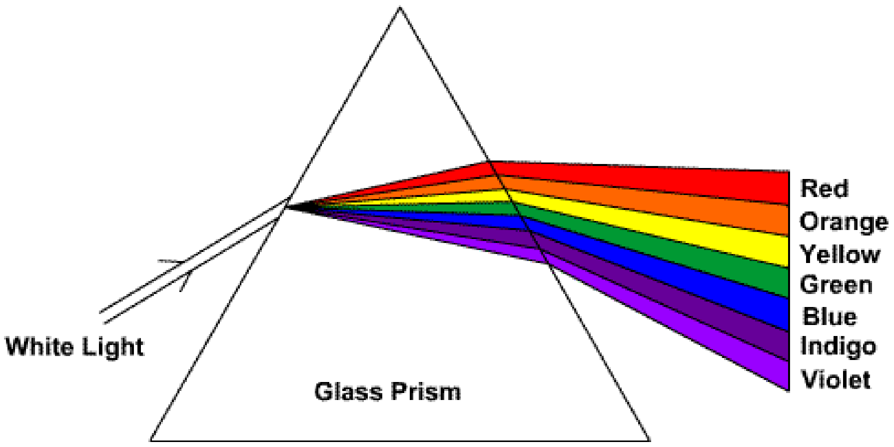


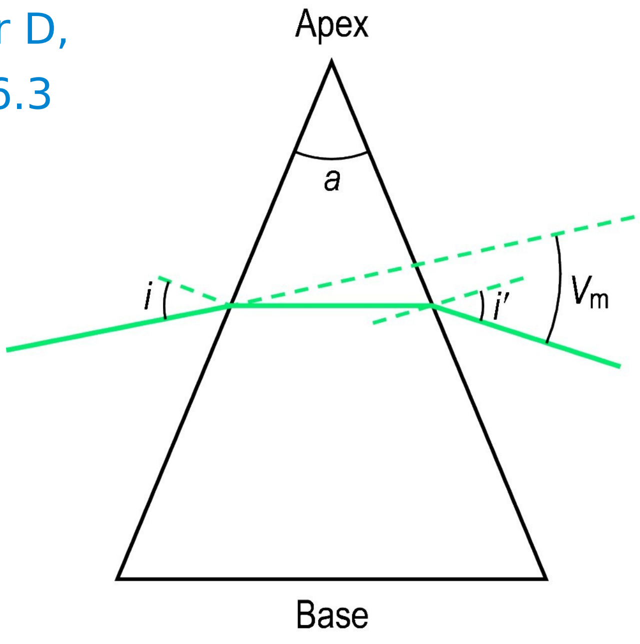
Prisms

- prisms disperse light by refraction
- red light is bent less than violet
- Abbe number V_D

$$V_D = \frac{n_D - 1}{n_F - n_C},$$

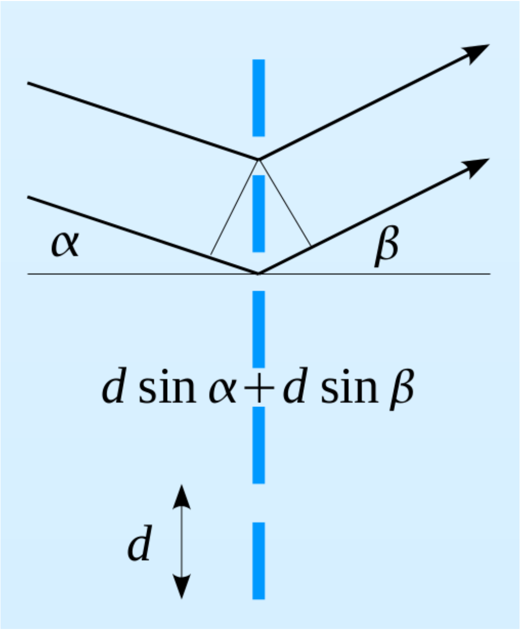
- where n_D, n_F, n_C are refractive indices for Fraunhofer D, F and C spectral lines (589.3 nm, 486.1 nm and 656.3 nm respectively)
- the larger the Abbe number the lower chromatic aberration (dispersion)





Diffraction gratings

- multi-slit diffraction and interference of light
- diffraction gratings: reflection and transmission
- most astronomical gratings are reflection type
- ruled (cut with ruling machines and replicated) vs. holographic gratings (cheaper alternative)
- the path difference between two successive grooves is d(sin α + sin β), where α - angle of incidence, β - angle of diffraction, d - grating spacing
- spectral order n quantifies how many wavelength differences are introduced between the successive grooves



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

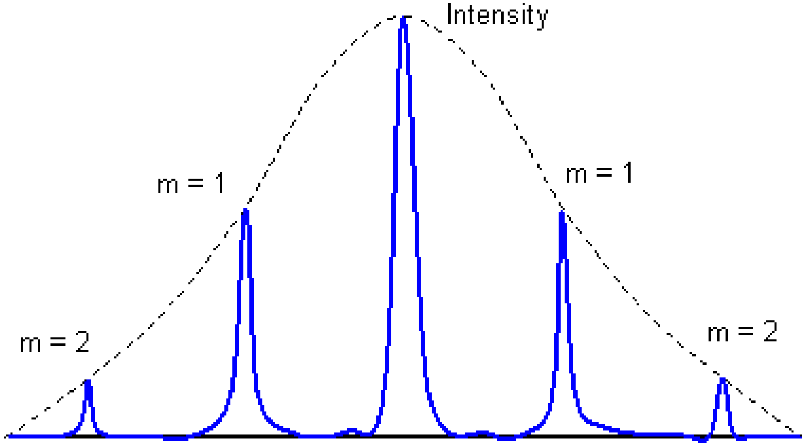
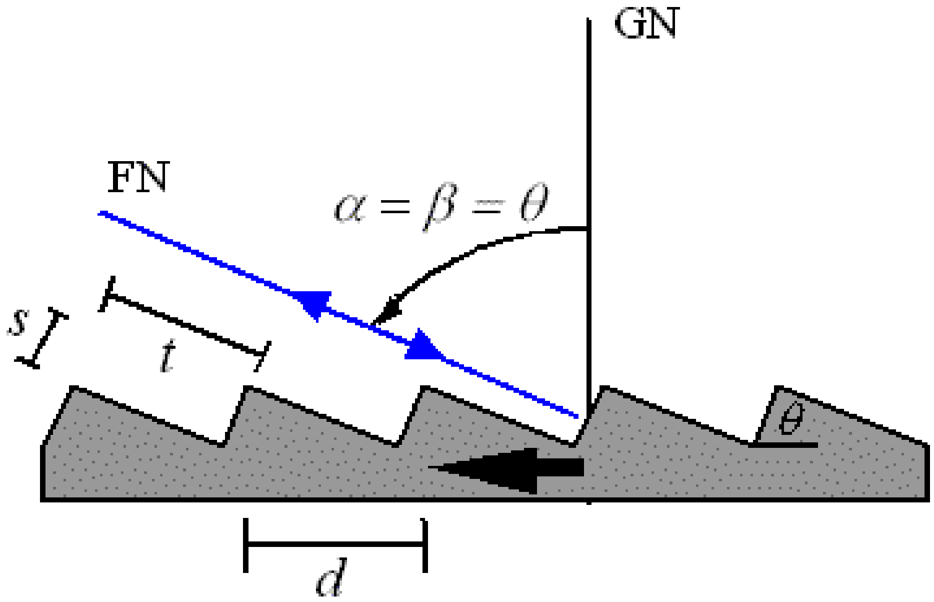


Figure 5

Blaze

- the maximum intensity of a transmission grating lies in 0th order where white light passes, the light is difracted to many orders...
- the intensity distribution is governed by difraction on the slits/grooves
- if the grooves of a reflection grating are inclined the intensity maximum is shifted away from 0-th order
- blaze angle θ determines the wavelength of maximum intensity
- échelle gratings, smaller number of grooves/mm but high interference orders are used, tg θ = R typically integer number, R2, R3, R4

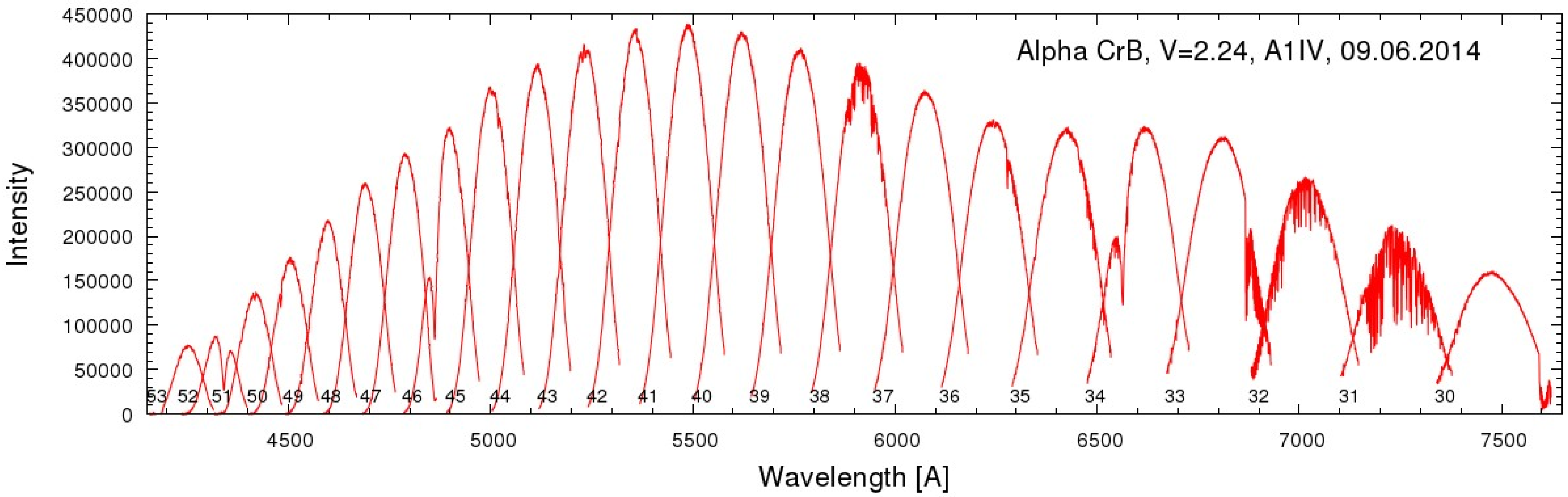


FN = facet normal
GN = grating normal

échelle intensity distribution aka blaze

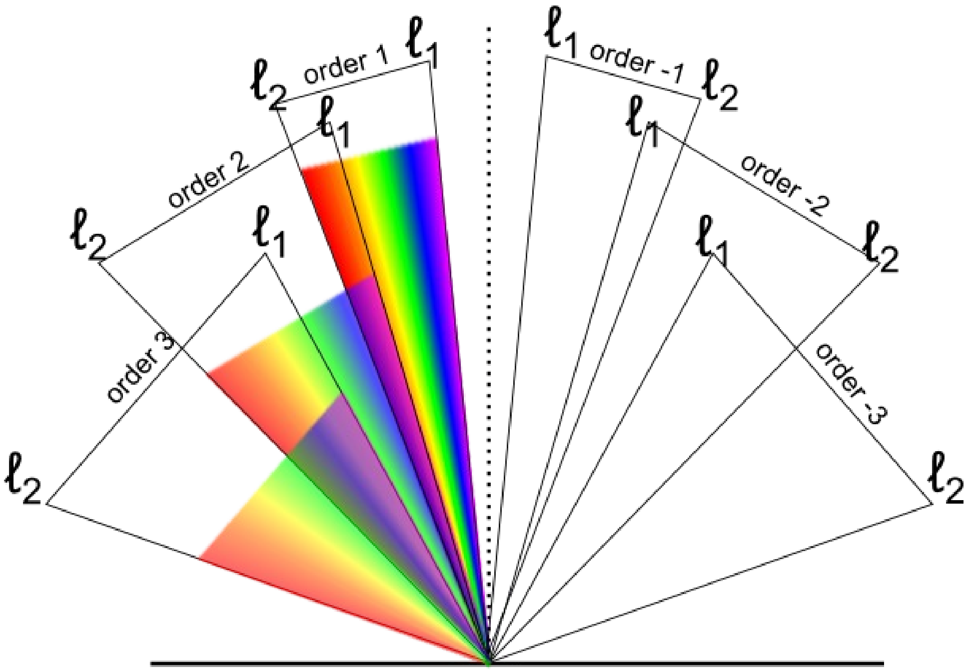
- Blaze function = distribution of intensity
- Order overlap, free spectral range = wavelength difference at the same β

$$I(\beta) = \left[\frac{\sin(\pi b \cos\phi[\sin(\alpha-\phi)+\sin(\beta-\phi)]\lambda}{(\pi b \cos\phi[\sin(\alpha-\phi)+\sin(\beta-\phi)]/\lambda} \right]^2$$



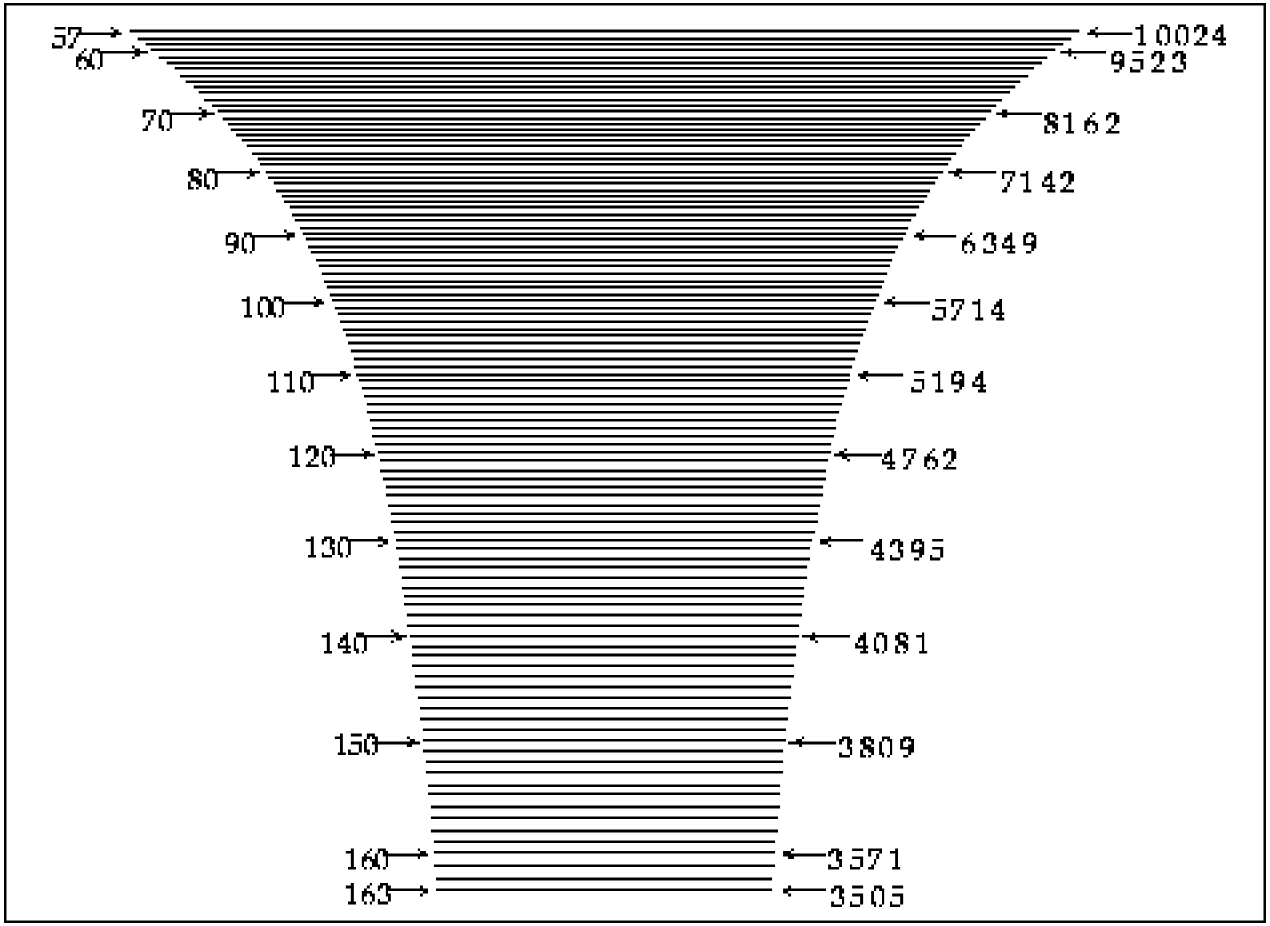
4. crossdispersers

- spectrum from interference orders overlaps
- in long-slit spectrographs 1st and 2nd orders are used - separated by filters
- in échelle spectra crossdispersers (prisms, grisms, gratings) are used
- prism has highest throughout



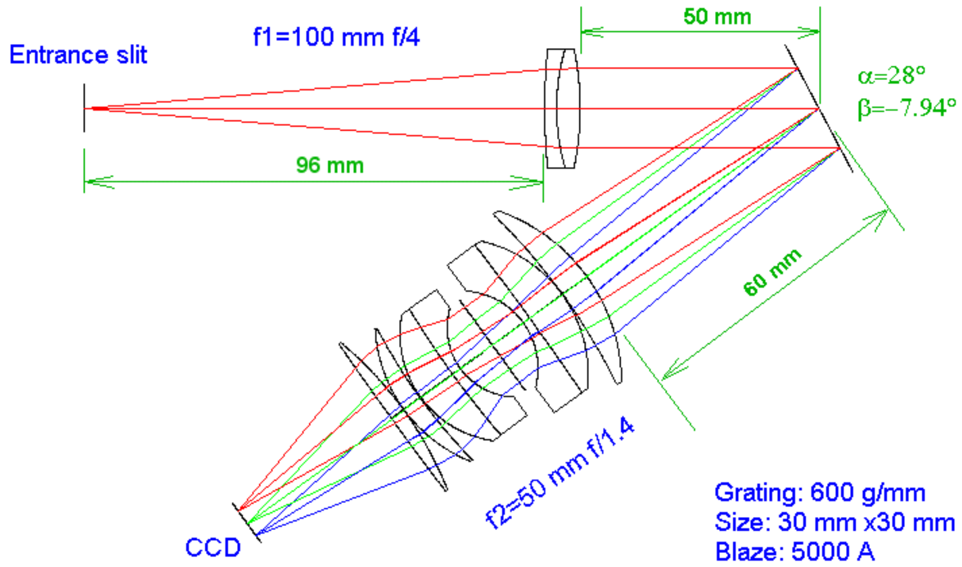
Echelle format

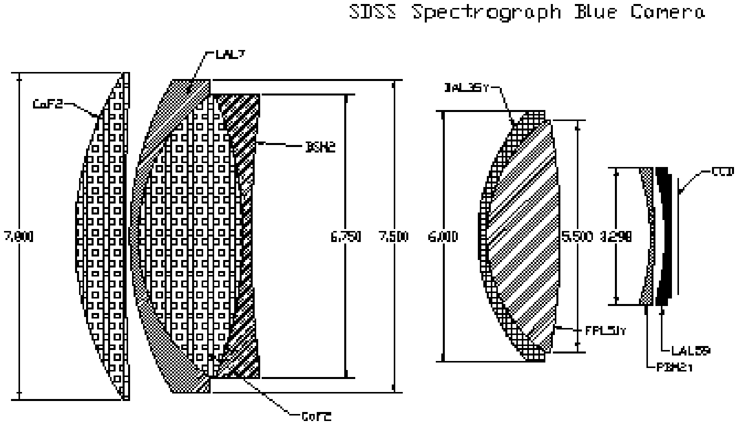
- Spectral orders width vs. crossdispersion
- prisms/gratings make crossdispersion non-equidistant



5. camera (=spectrum focusing lens)

- parallel beam is converted to convergent
- images the spectrum produced by the dispersion element on a detector
- necessary to image rays far from optical axis and of widely different wavelength
- the focal length of the camera vs. CCD chip size vs. spectrum size



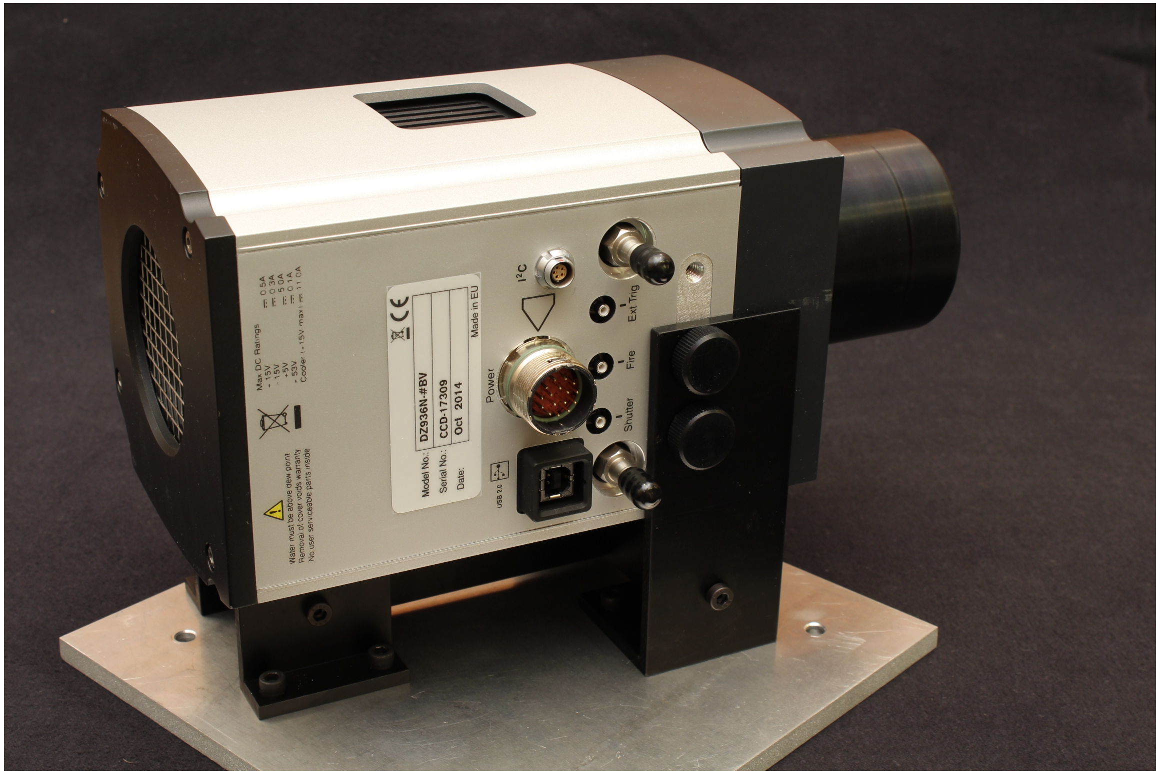


Camera types

- reflecting cameras (Schmidt) have central obscuration but wide wavelength range
- lens cameras (e.g. photolense): no central obscuration, need many elements = low throughput
- two-channel spectrographs: camera optics optimized for a narrower wavelength range = smaller absorption

6. focal detector

- in the focal plane of the camera
- for highest SNR we need low read-out noise, high QE CCDs, low dark currents -> cooling and vacuum issues
- 2-3 pixels per FWHM of spectral resolution
- in long-slit systems the longer side of the chip is along the dispersion axis
- in échelle spectrographs square chips



Important issues/common caveats

Achieving high spectral resolution

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

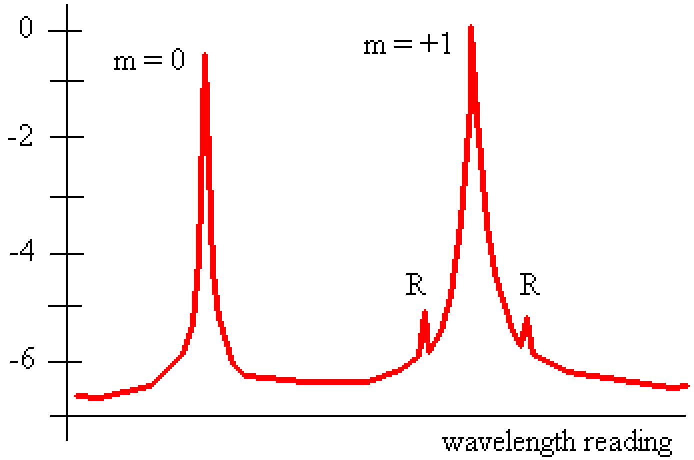
$$R = \frac{f_{\mathrm{coll}}}{w} \frac{n^2}{d^2} \left(\frac{\sin\alpha + \sin\beta}{\cos\alpha} \right)$$

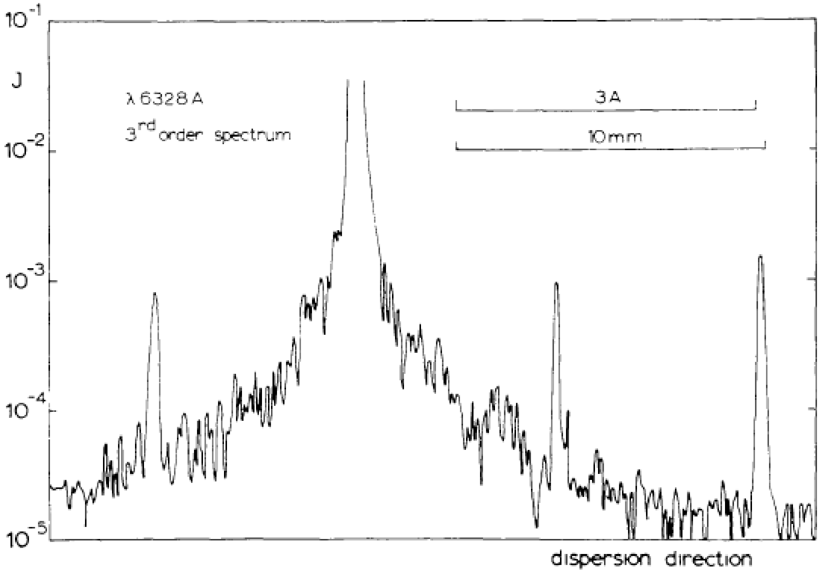
The spectral resolution depends on:

- interference order, n
- grating spacing, d
- grating resolution, given by total number of grooves
- angular size of the slit image as seen by the collimator w/f_{coll}
- sufficiently small CCD pixels

Spectral resolution and instrumental profile

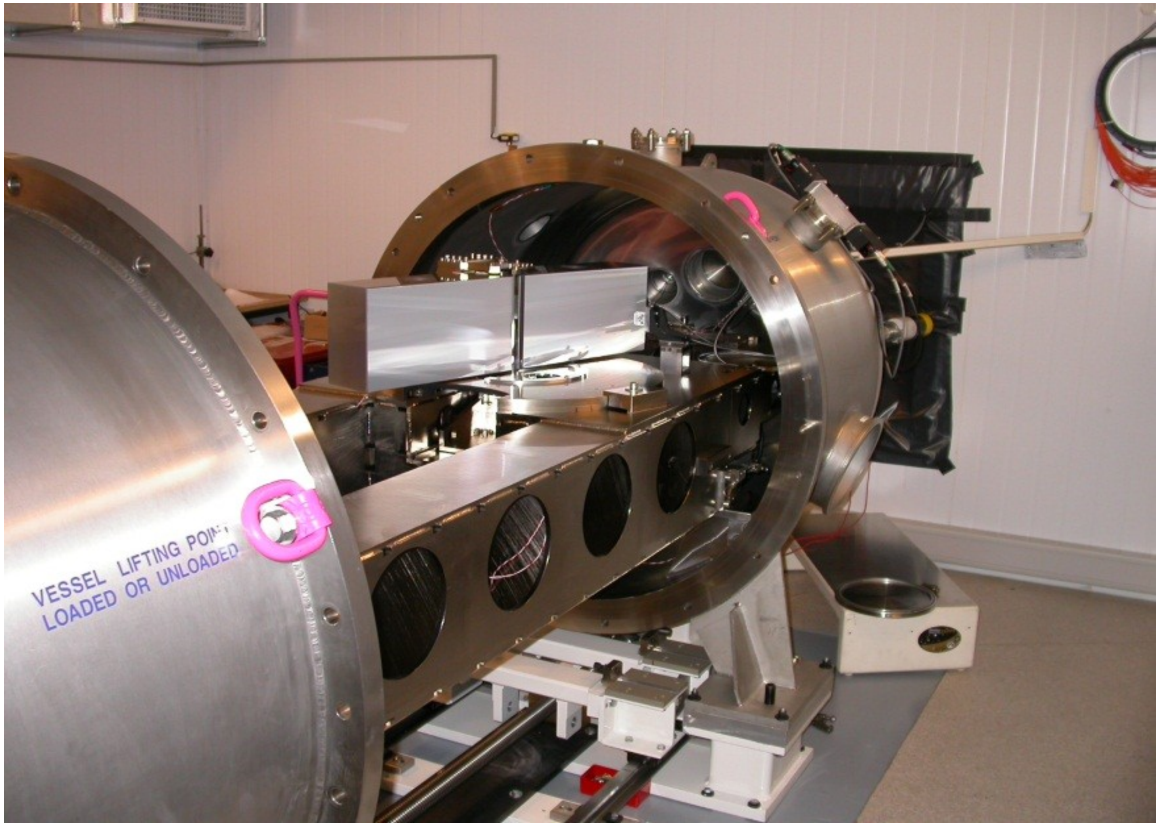
- response of the spectrograph to a monochromatic light (delta function)
- observed spectrum = convolution of the instrumental profile and the stellar spectrum
- IP for low-resolution instruments can be estimated from lamp lines
- IP for high-resolution work using lasers
- grating ghosts and light scatter
- with lamp spectra astigmatism of the camera can be estimated
- FWHM(IP) = resolution





Achieving high RV accuracy

- $\Delta RV = 1$ m/s
- $\Delta\lambda = 0.00002$ Å
- 15nm on CCD
- 1/1000 of pixel

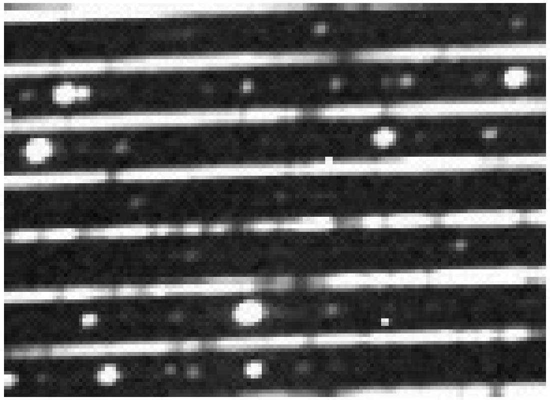


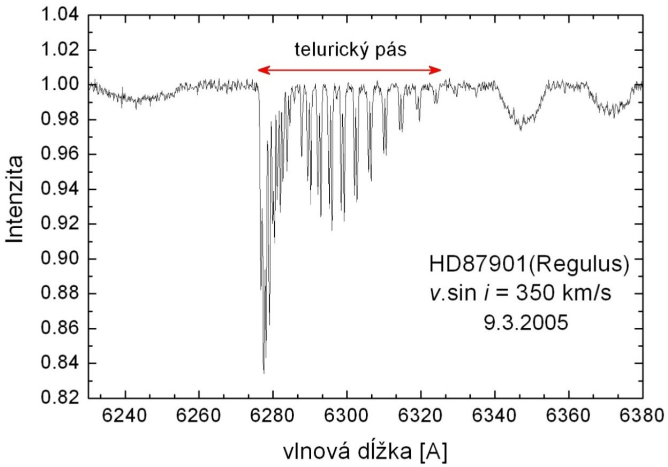
- $\Delta RV = 1$ m/s
- $\Delta T = 0.01$ K
- $\Delta p = 0.01$ mBar

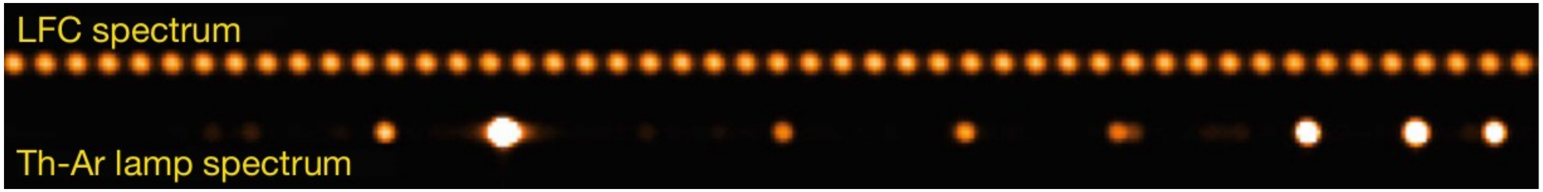
high optomechanic stability, high resolution, correct wavelength calibration

High RV-accuracy techniques

- Image scrambling, changes in guiding on a slit shift the RV system
- Iodine cell
- simultaneous ThAr
- laser combs - promise 10cm/s accuracy
- telluric bands - limited to about 100 m/s accuracy but freely provided by the atmosphere





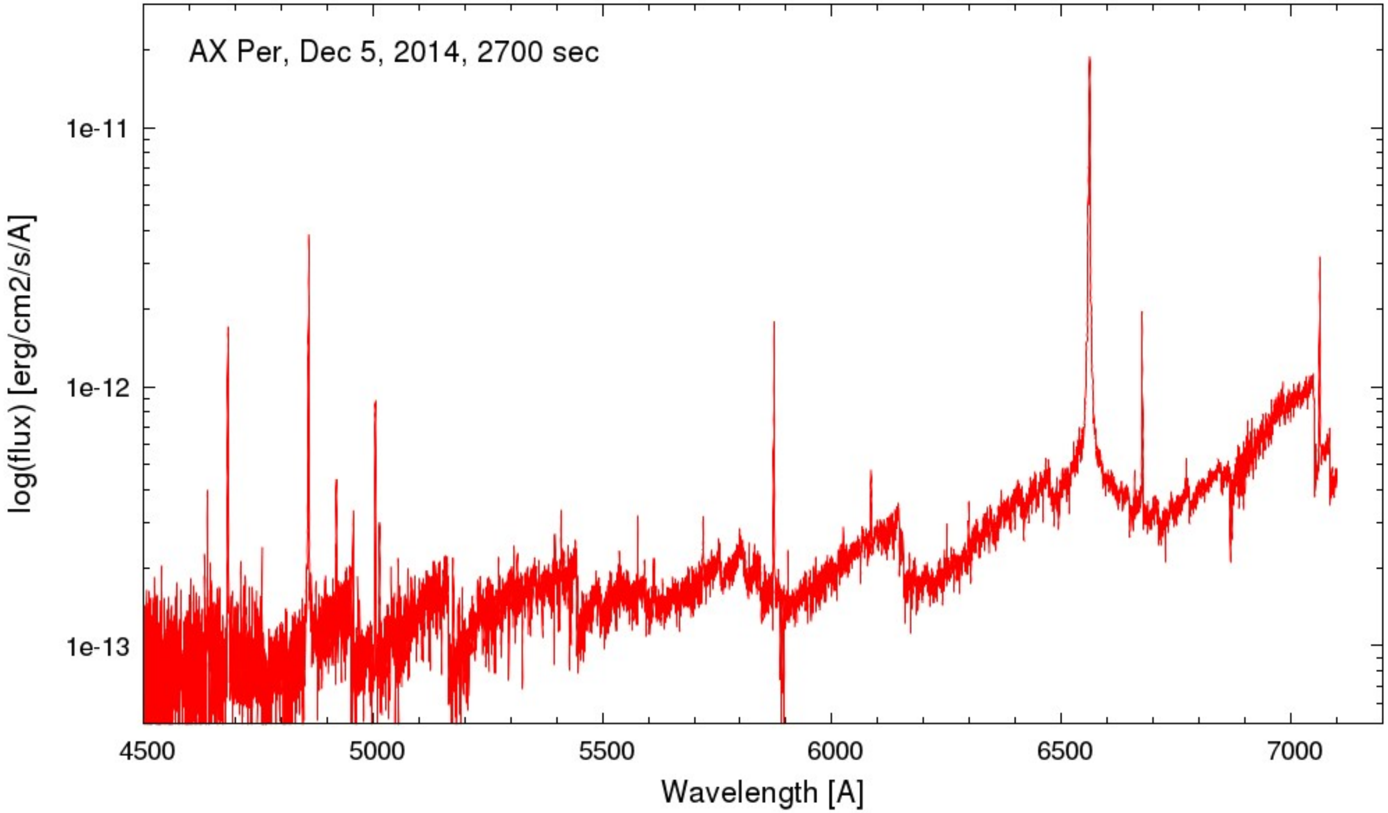


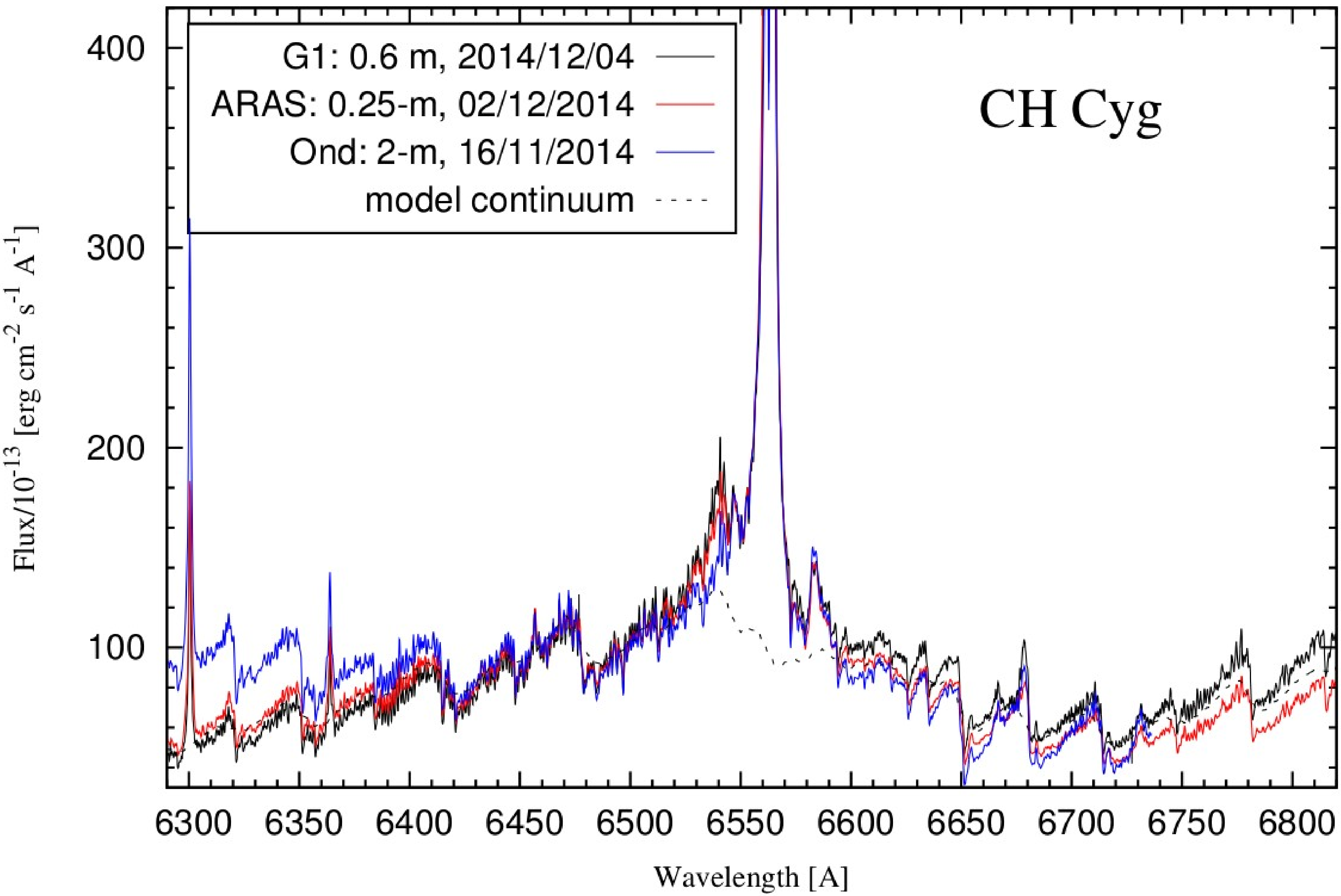
Spectrograph throughput

- multiply the efficiency of all components
- fiber throughput, reflectance of coatings, gratings, lens transmission, detector efficiency
- e.g. for eShel: guiding unit and fore-optics 59%, fiber input 71%, spectrograph 21% => 8%

Spectrophotometry

- Calibration to fluxes, e.g. erg/s/m^2/Å using spectrophotometric standards
- Complicated by (i) fiber opening/slit/guiding loses, (ii) chromatic atm. refraction (for low X), (iii) atmospheric extinction, $k = k(\lambda)$ (iv) blaze function
- Difficult with échelle spectrographs: blaze function hard to fully rectify
- long slit and low-dispersion spectrographs ideal to use parallactic orientation
- Multi-color photometry improves the fluxes





G1: 0.6 m, 2014/12/04
ARAS: 0.25-m, 02/12/2014
Ond: 2-m, 16/11/2014
model continuum
CH Cyg
Flux/10^-13 [erg cm^-2 s^-1 A^-1]
Wavelength [A]
100
200
300
400
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800

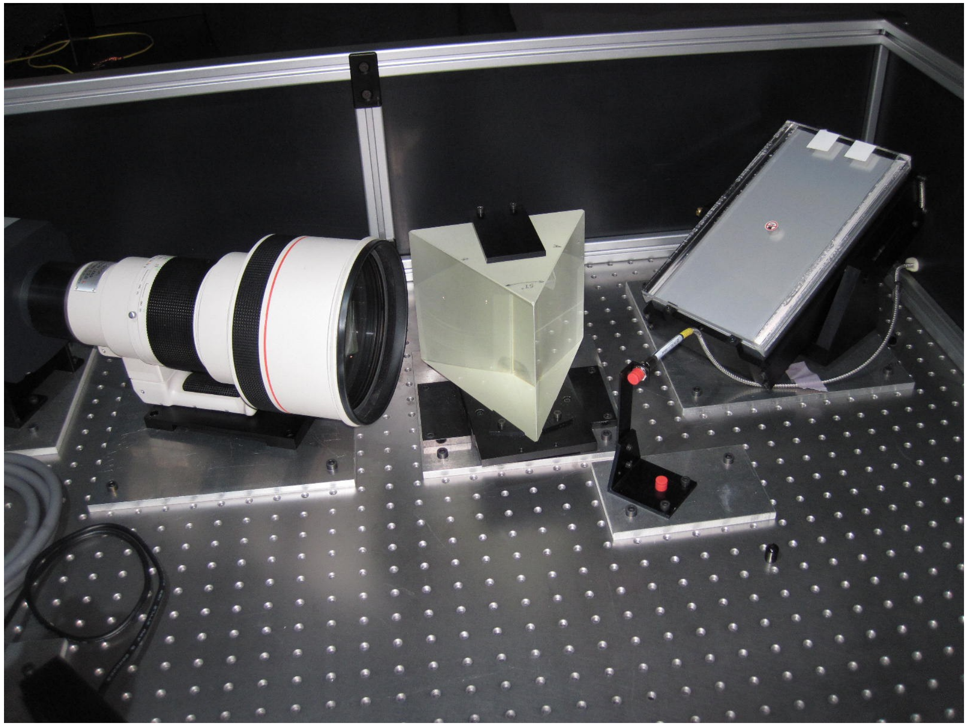
Optical spectrographs at AI SAS

eShel spectrograph design & parameters

- Littrow design with f/5, prism cross-disperser, 125mm collimator
- fiber-fed
- R2 échelle grating, 79 grooves/mm
- spectral resolution R=11000
- useful spectral range: 24 orders covering 4100-7600 Å
- Canon f/1.8 lens: chromatic aber.
- 50 micron object fiber, 200 micron calibration fiber
- calibration lamps: ThAr, Tungsten, blue LED
- CCD detector: ATIK 460EX camera, ron = 5.1 e-, gain 0.26, 2749 x 2199 pixels, 4.54 µm pixel
- f/6 FIGU, WATEC 120n guiding camera

MUSICOS spectrograph @1.3m telescope

- Littrow design
- fiber-fed
- grating 31.6 lines/mm, R2 échelle, 120x250mm
- SF5 glass prism with 57° apex angle
- f/4 on-axis collimator
- spectral resolution R=35000
- useful spectral range: 57 orders covering 4200-7300 Å
- Canon f/2.8 400mm lens
- 50 micron object fiber, 200 micron calibration fiber
- calibration lamps: ThAr, Tungsten, blue LED
- CCD detector: Andor iKon 936 DZ
- f/6 FIGU, WATEC 120n guiding camera



Thanks for your attention !