High Resolution Spectroscopy

NEON School

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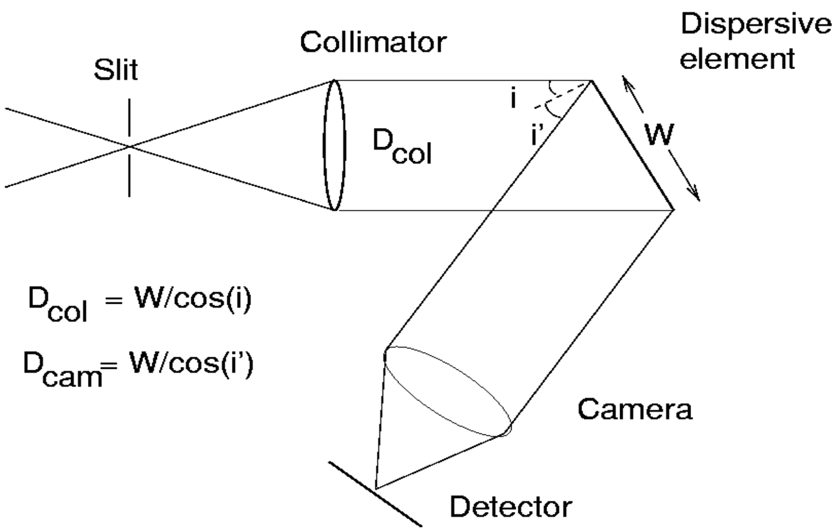
Spectrographs

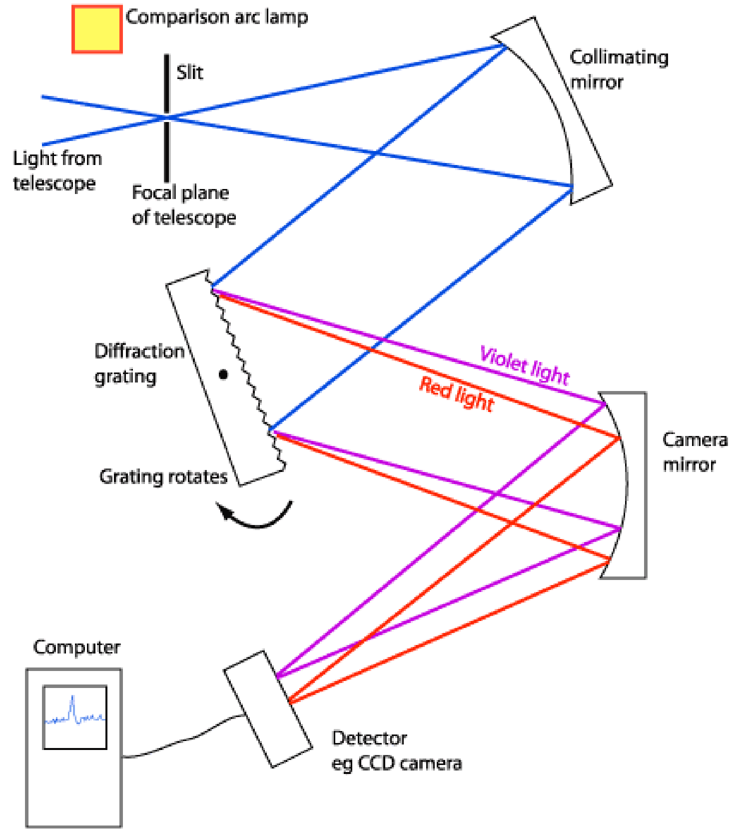
Contains:

- a slit
- a disperser element
- a detector



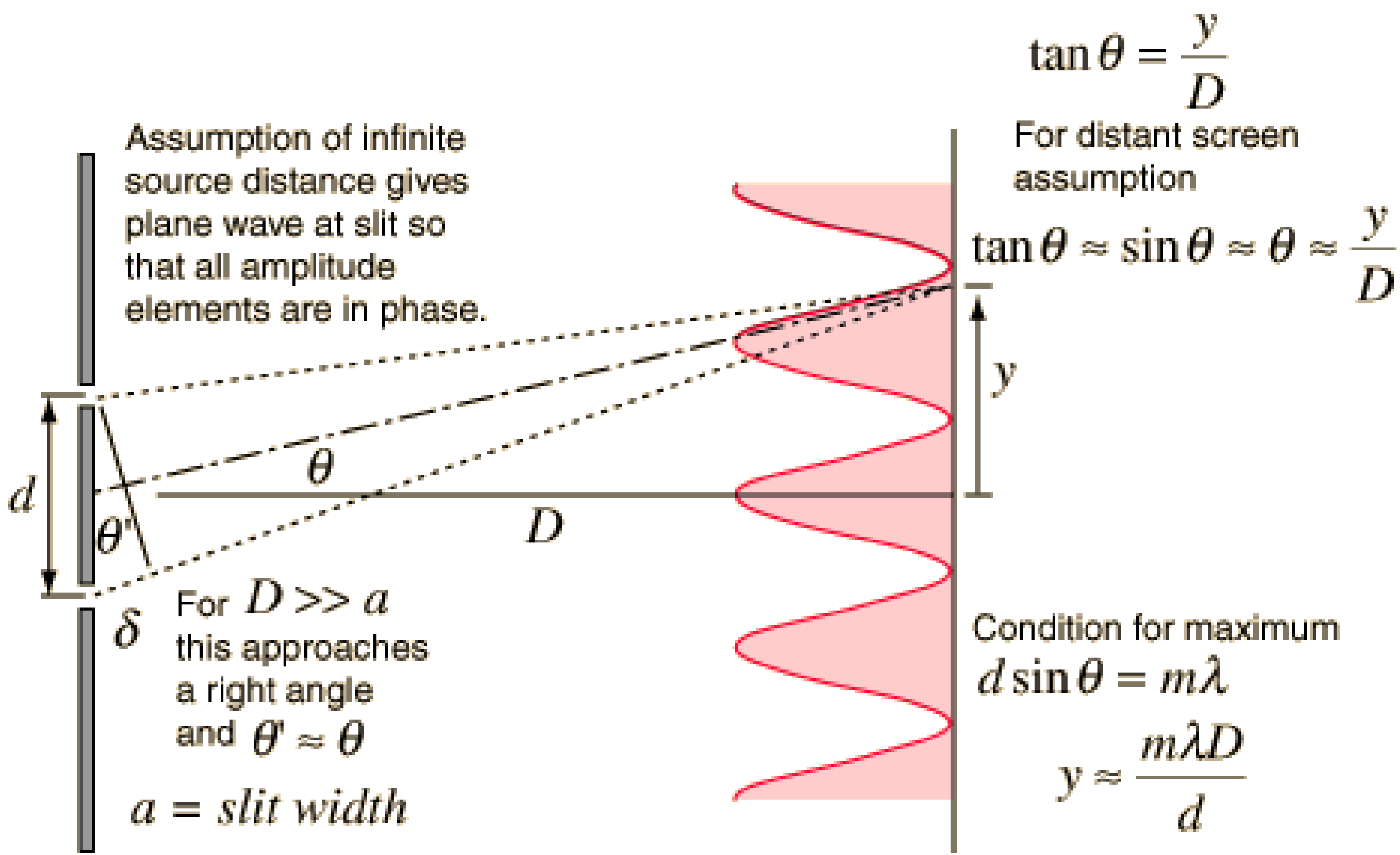
$D_{col} = W/\cos(i)$

$D_{cam} = W/\cos(i')$

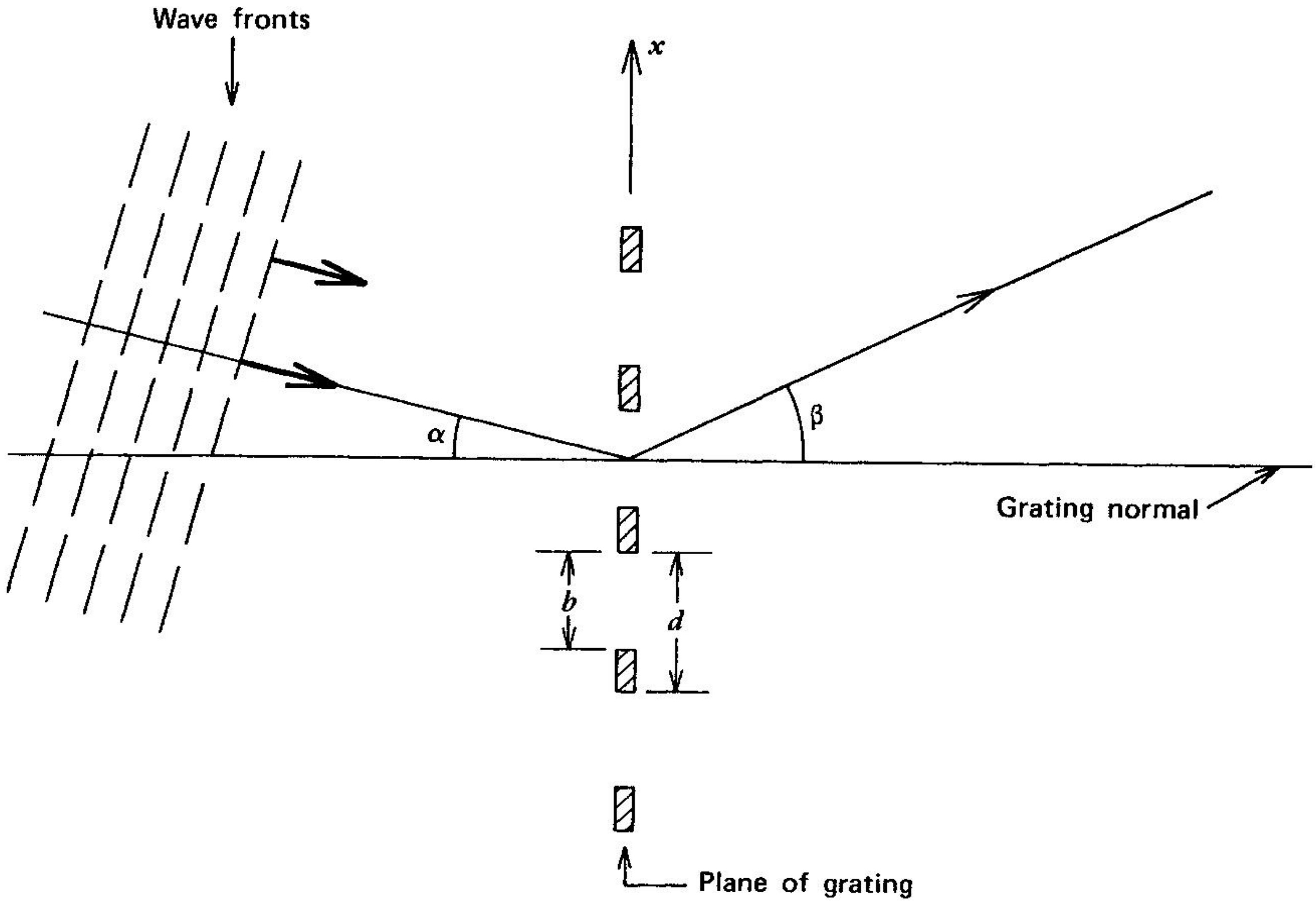


A Schematic Diagram of a Slit Spectrograph

Double slit interference



Schematic grating



Grating equations (1/2)

Incident wave equation: $F(x,t) = F_0(t)\exp\left(\frac{2\pi i x \sin\alpha}{\lambda}\right)$

Transmission function: $G(x) = 1$ if $x \in b$, 0 if $x \notin b$

Resulting wave function: $g(\beta) = \int_{-\infty}^{+\infty} F(x,t)\, G(x) \exp\left(\frac{2 i \pi \sin\beta}{\lambda}\right) dx$

$$g(\beta) = F_0(t) \int_{-\infty}^{+\infty} G(x) \exp\left(\frac{2 i \pi x}{\lambda}(\sin\alpha + \sin\beta)\right) dx$$

which is the TF of $G(x)$

Grating equations (2/2)

The maxima of $g(\beta)$ are for $(sin\,\alpha + sin\,\beta) - \frac{m\lambda}{d} = 0$
where m is the grating order

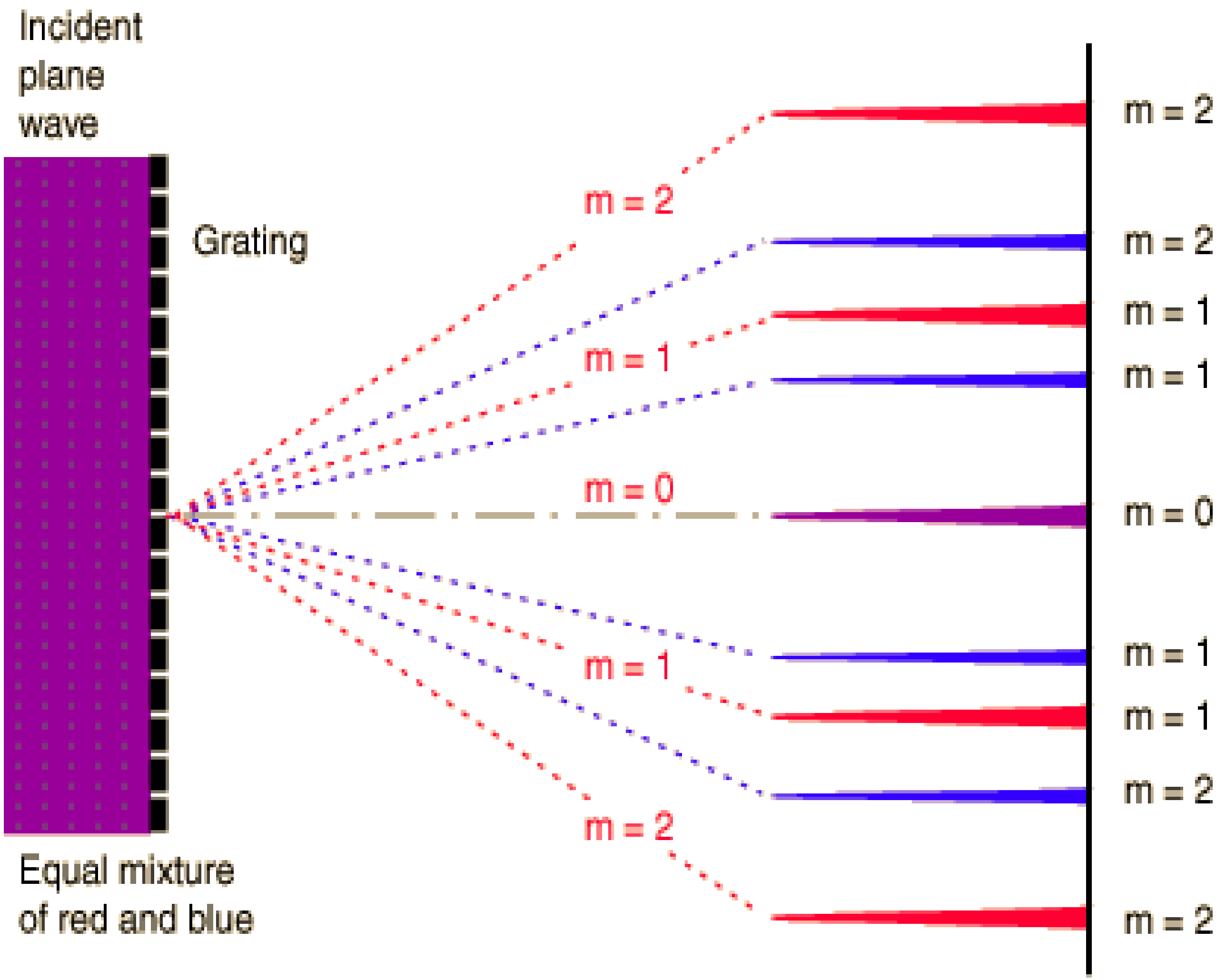
$$\frac{m\lambda}{d} = \sin\alpha + \sin\beta$$

The angular dispersion is thus:

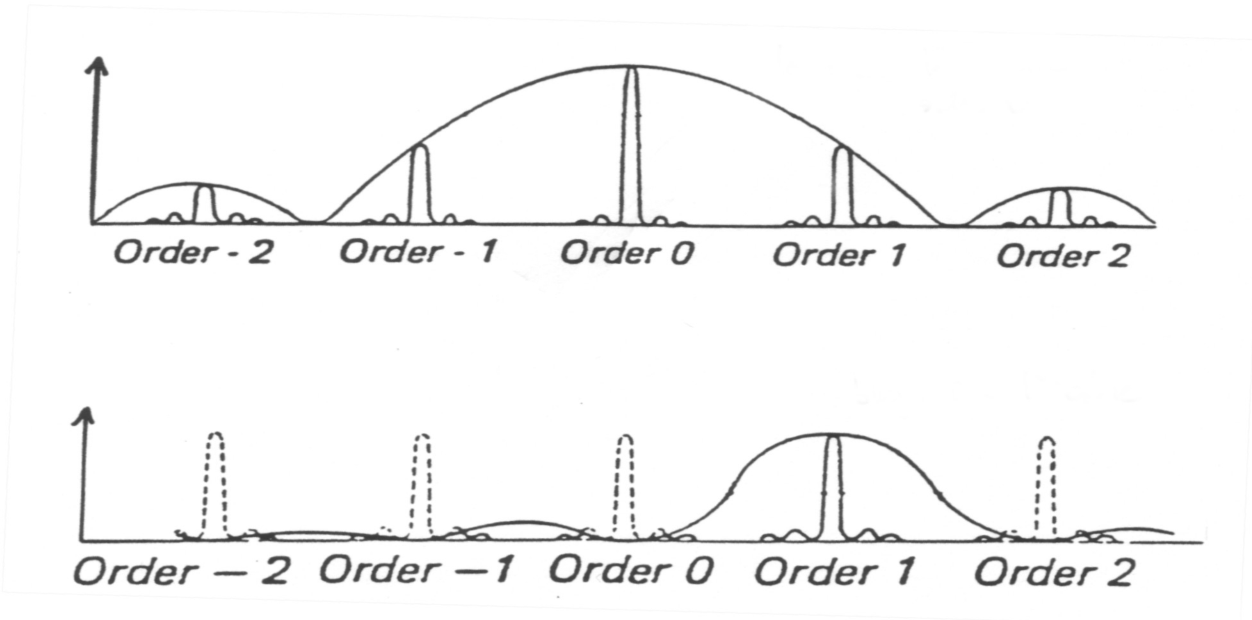
$$\frac{d\beta}{d\lambda} = \frac{m}{d\,cos\,\beta}$$

Diffraction gratings

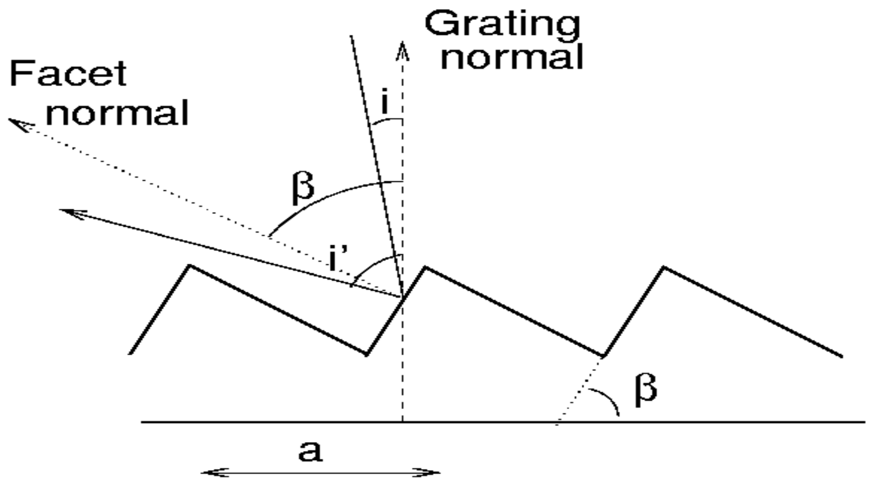
m is the order

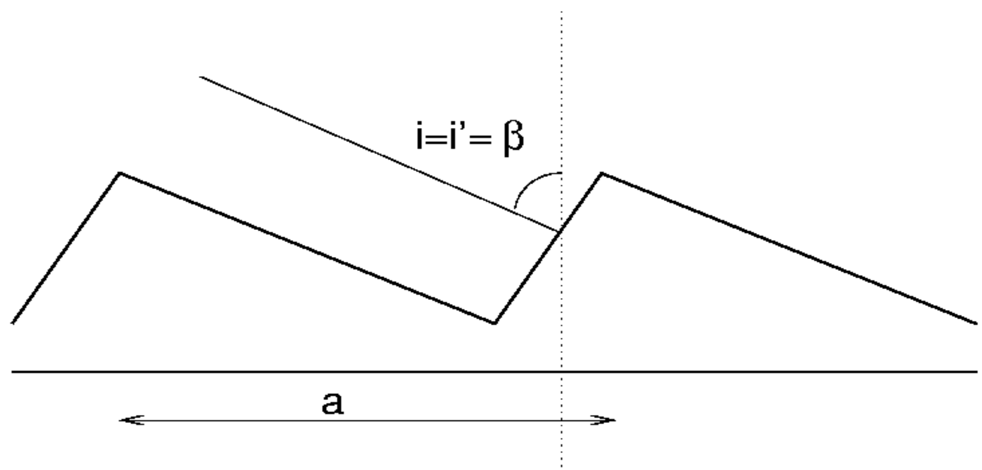


Ex: Blazed grating at order 1



Blaze & Echelle gratings

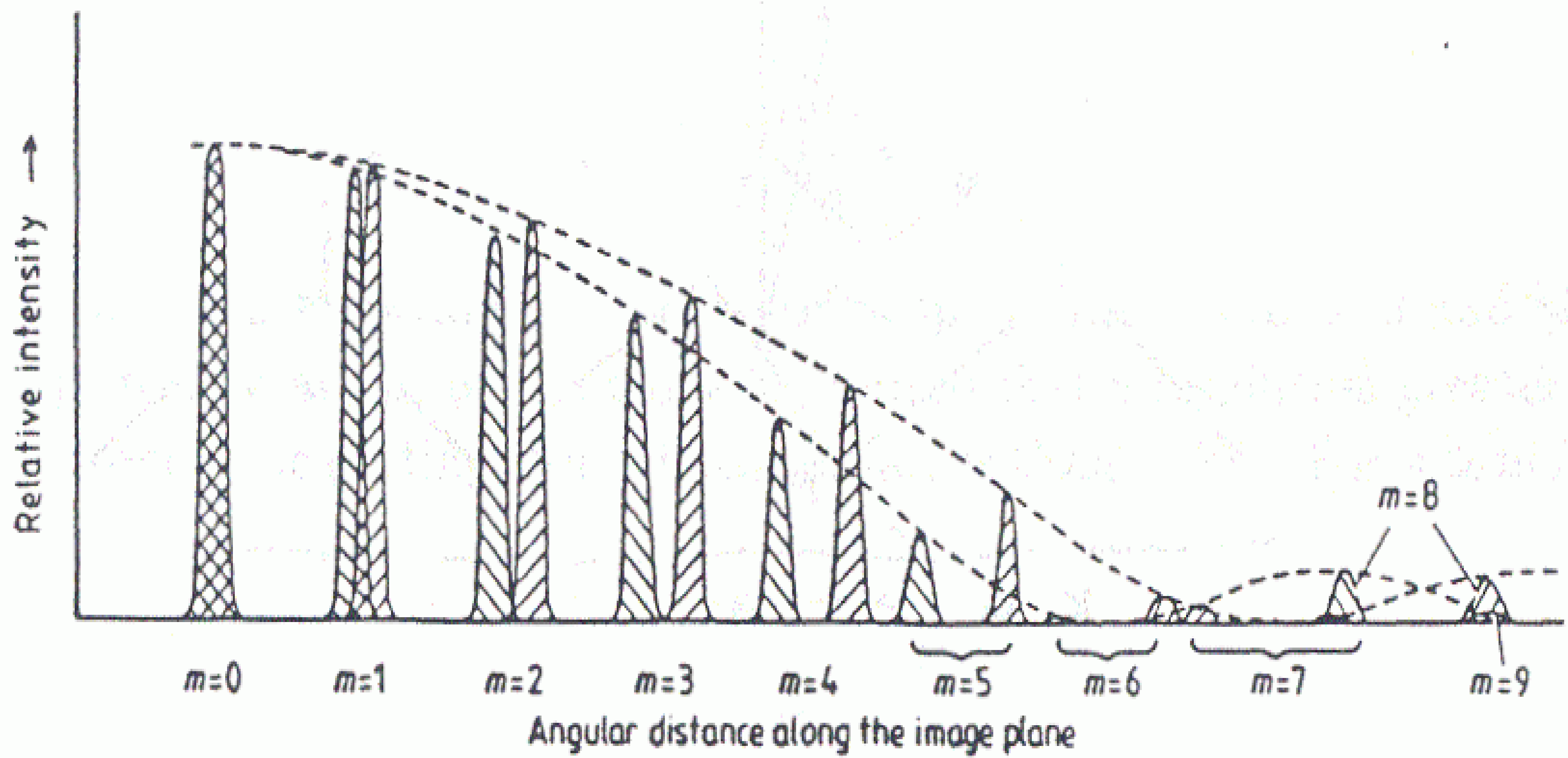




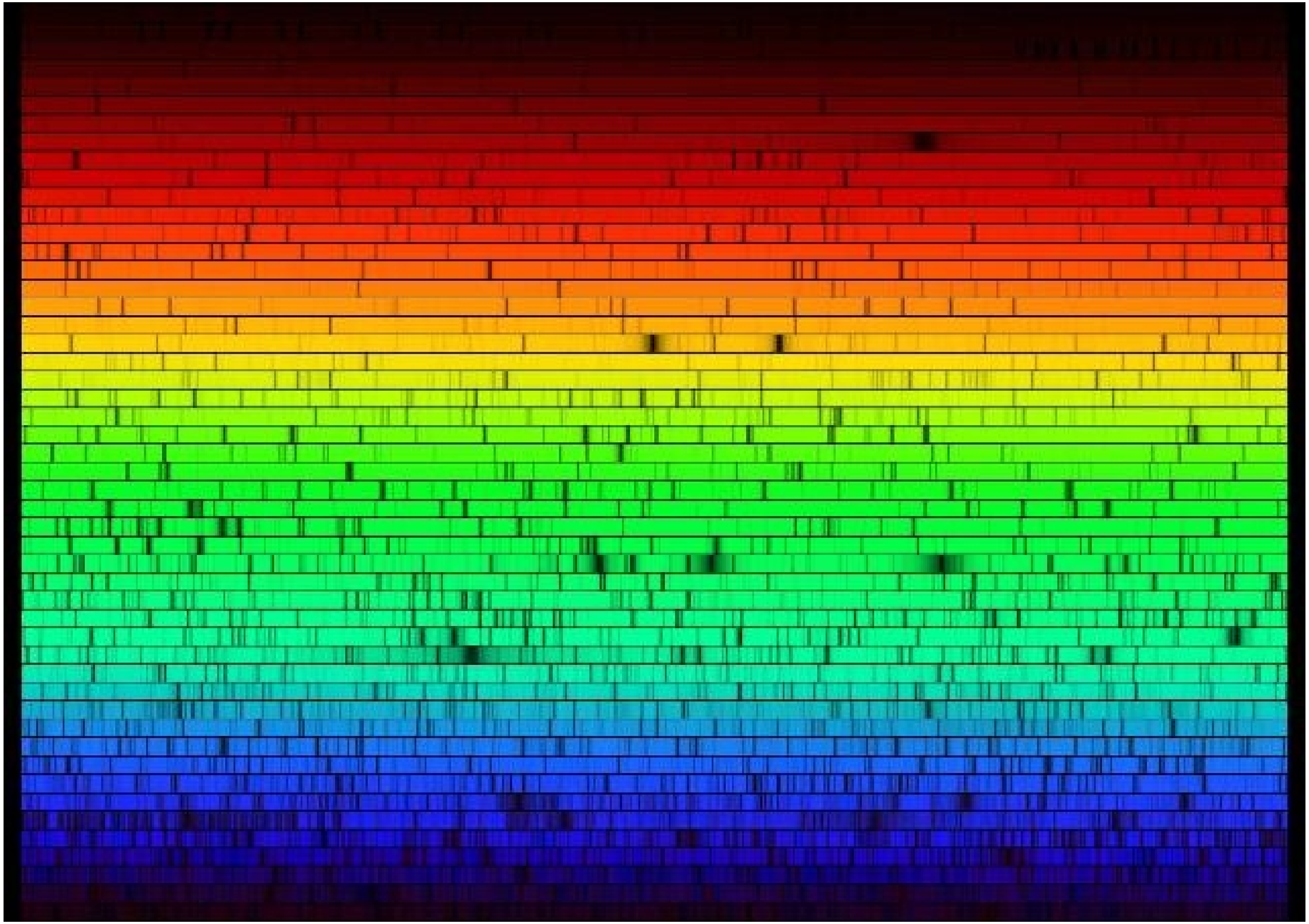
Blazed angle of a grating: allows to redirect maximum light towards a given order

Echelle grating: small incidence angle: allows to work in a large order: increase of spectral resolution

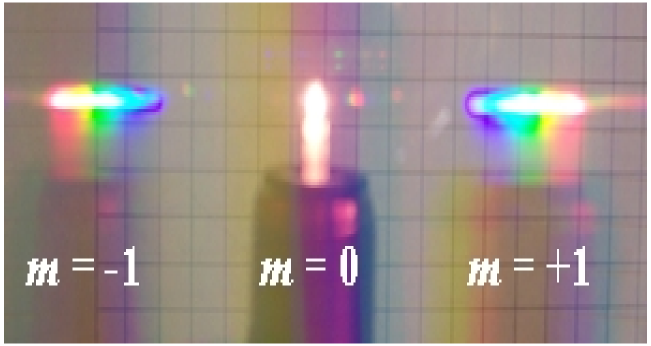
Diffraction envelope

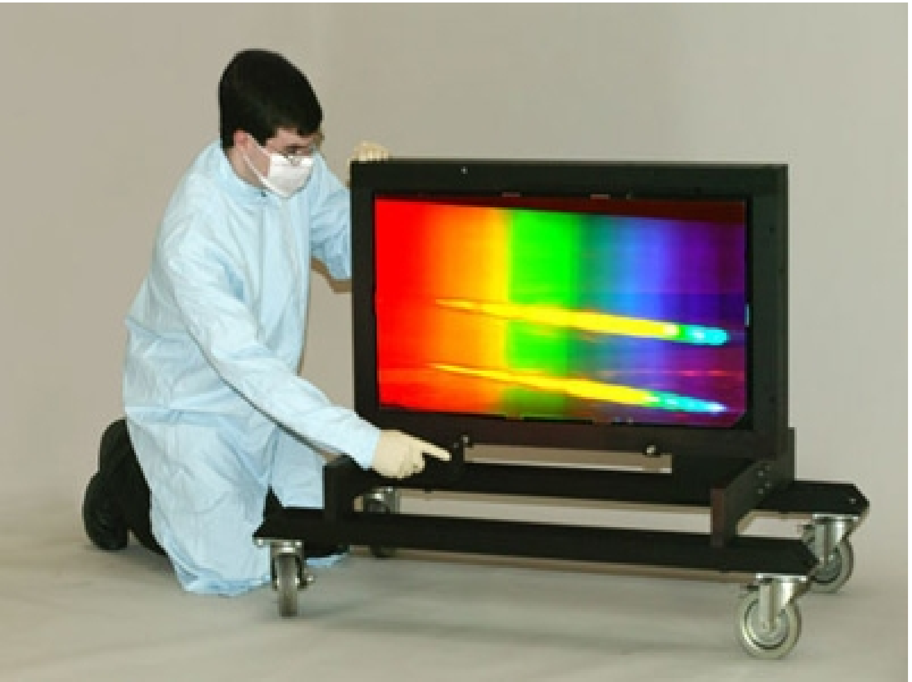


Echelle spectrum



Gratings...

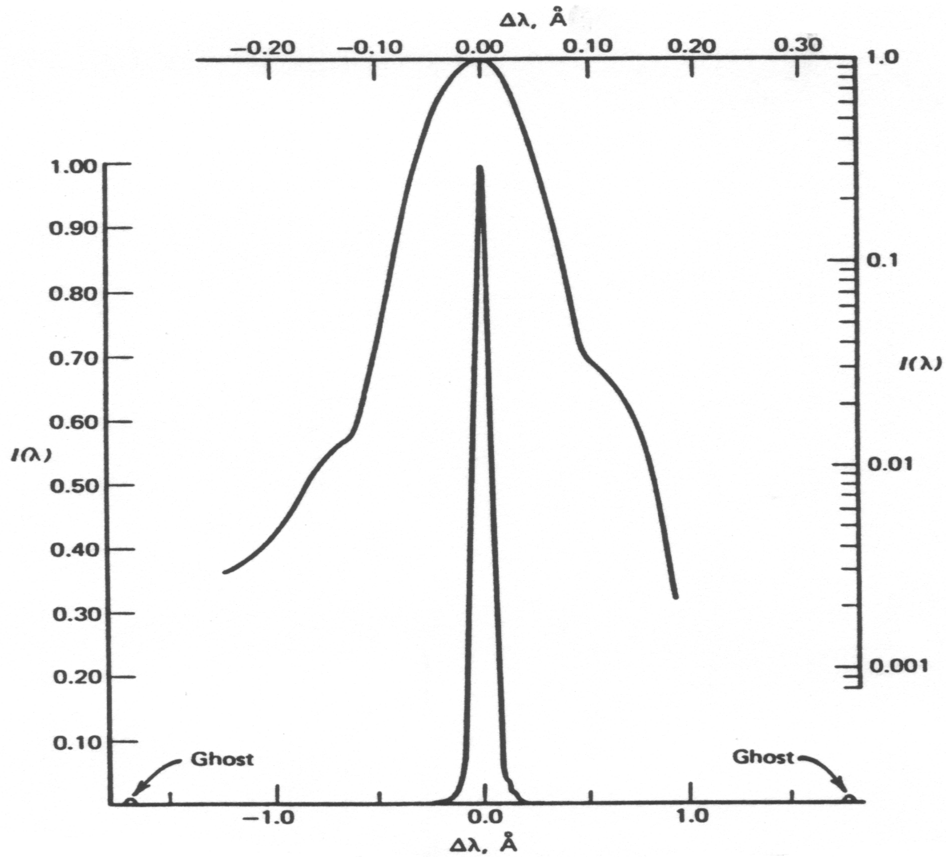




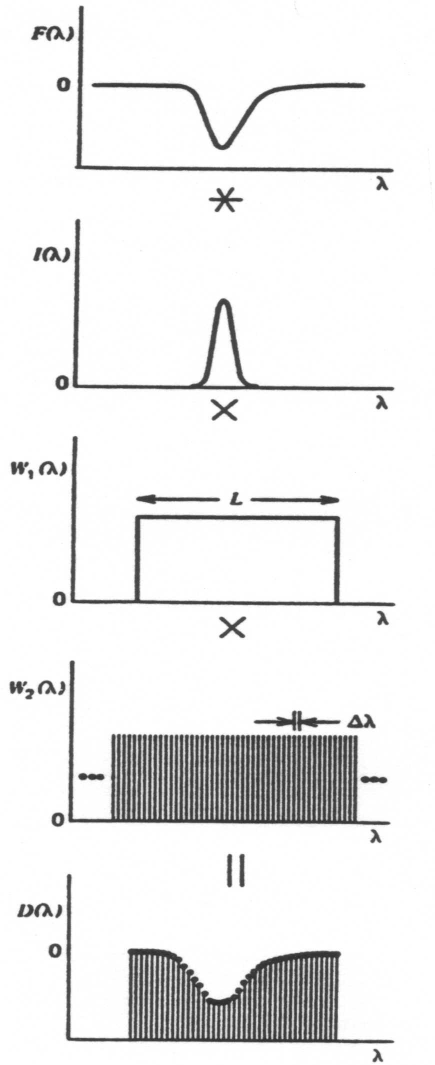
Instrumental profile

The spectrograph is not perfect: the light beam is affected by various phenomena such as diffusion, diffraction, resolution, aberrations...

➡ One need to determine the instrumental profile:



What do we measure?



Real stellar spectrum

Instrumental profile

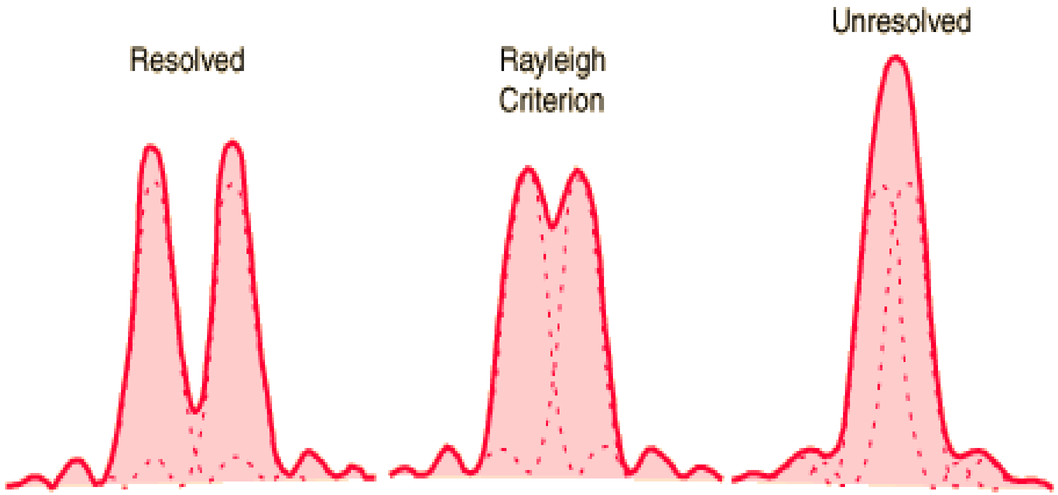
Detection domain

Sampling function

Observed stellar spectrum

Resolvance of a grating

Follows the Rayleigh criterion: 2 wavelengths are resolved when the maximum of ones lies at the first minimum of the other :



Angular Rayleigh criterion: $\Delta\theta = \dfrac{\lambda}{N\, d \cos\theta}$

Dispersion and resolution

The resolving power is defined as: $R = \frac{\lambda}{\Delta\lambda}$ where $\Delta\lambda$ is the smallest wavelength difference

From the dispersion equation: $R = mN$

NOTE: R is independent of the wavelength:

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

Choice of the resolving power

Practical criterion: choose $\Delta\lambda \ll$ smallest structure to be observed

Most of astrophysical media produce lines larger than the Doppler width:

$$W_D[\AA] = 7.162\,10^{-7}\,\lambda\,\sqrt{T/\mu}$$

Where μ is the atomic mass ➡ temperature dependence

Temperature dependence

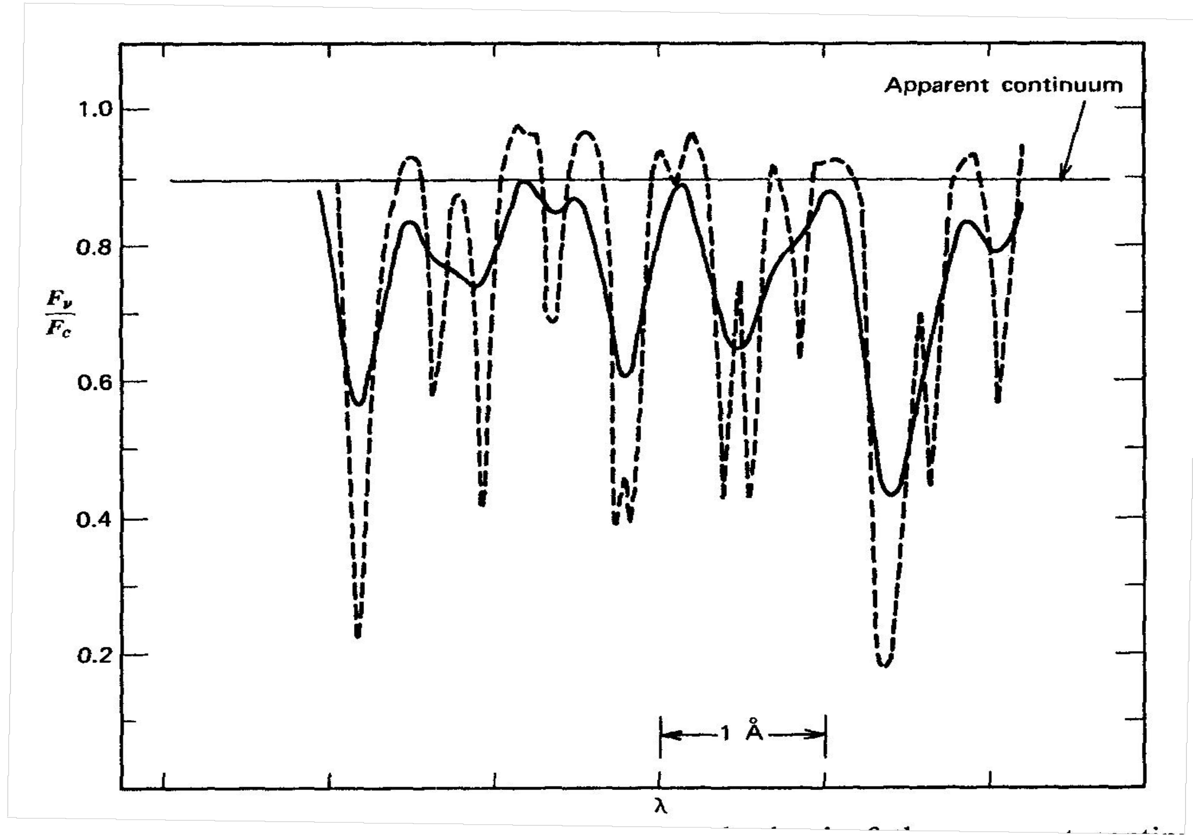
T_e (K)	10^2	10^3	10^4	10^5	10^6
Typical for	cool interstellar medium circumstellar shells	planets	photospheres shells around hot stars	transition regions	coronae
FWHM(Å) for Hβ	0.06	0.13	0.36		
R =	80 000	40 000	10 000		
FWHM(Å) for Fe I at 5000 Å	0.005	0.015	0.05	0.15	0.48
R =	1 000 000	300 000	100 000	30 000	10 000

Choice of the resolving power

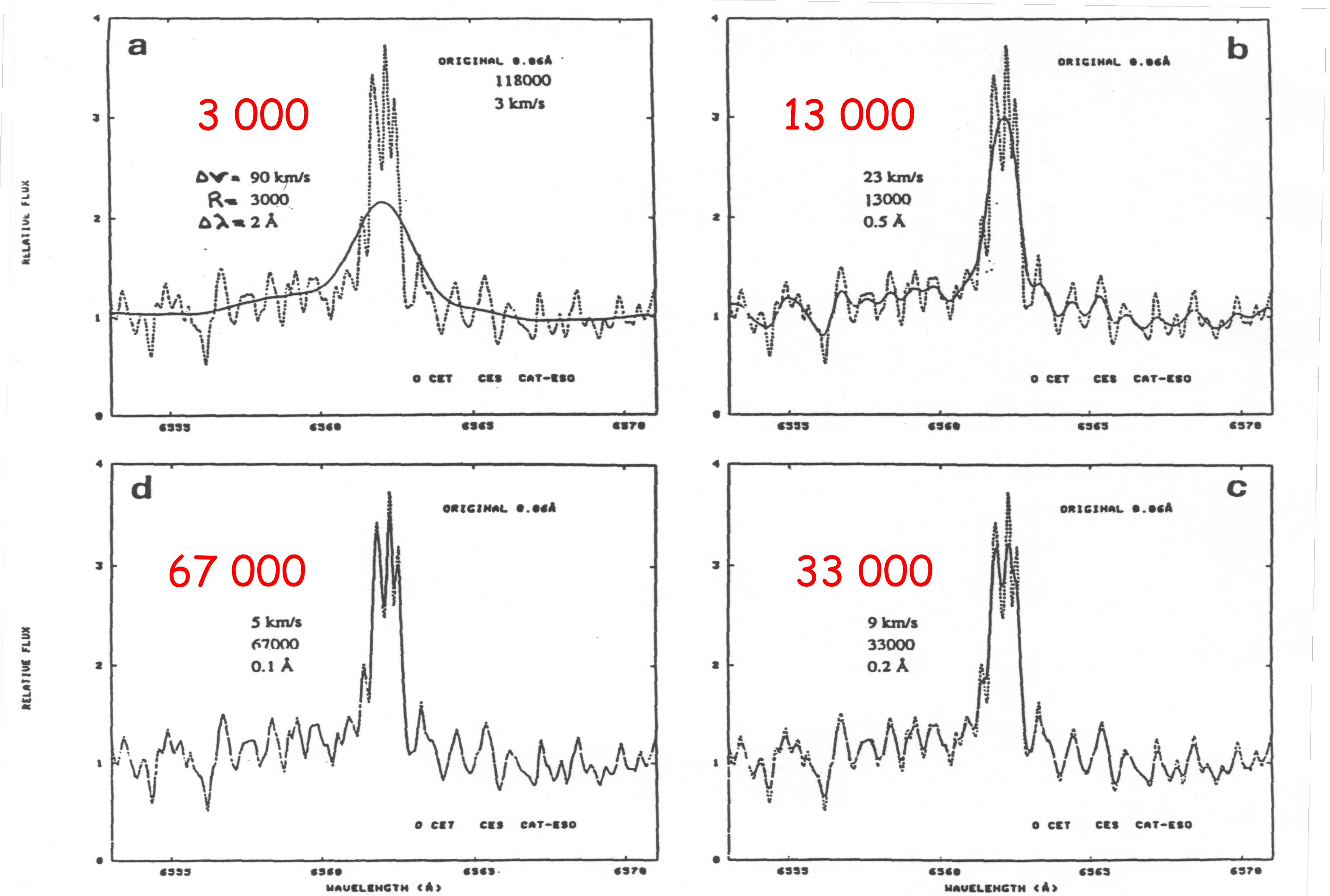
Choosing a too low resolution:

• influence of noise

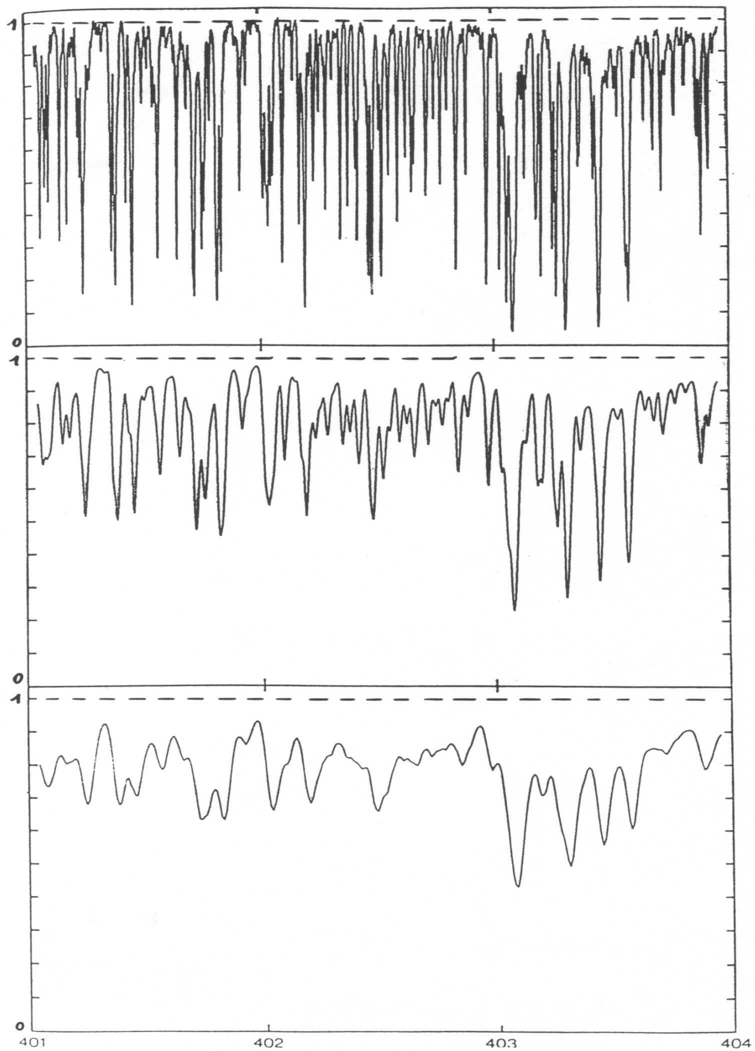
• influence of blends



Importance of R



Importance of R



R = 300 000

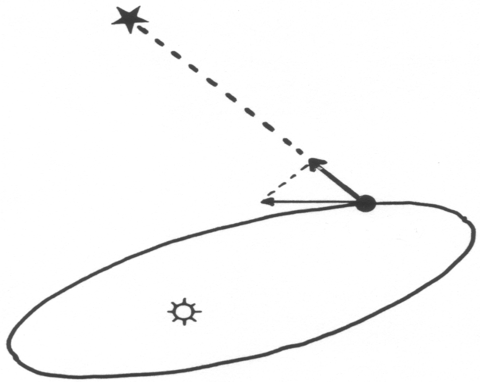
R = 23 000

R = 8 000

Reduction : main steps

- offset subtraction
- dark subtraction
- [orders localisation]
- Flat-field correction
- wavelength calibration
- cosmic remove
- flux calibration or continuum normalization
- deconvolution from instrumental profile

Velocity and light-time correction



Star's heliocentric velocity =

Star's observed velocity + $V_{correction}$

$V_{correction} = V_{diurnal} + V_{orbital}$

$V_{diurnal} = -0.4654 \sin h \cos \delta \cos \varphi$ km/s

$V_{orbital} = \dot{X} \cos \alpha \cos \delta + \dot{Y} \sin \alpha \cos \varphi + \dot{Z} \sin \varphi$ km/s

where h = hour angle

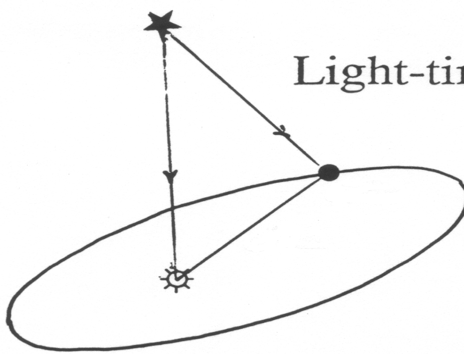
φ = latitude

α, δ = right ascension and declination

X, Y, Z = rectangular coordinates of the Earth with respect to the barycentre of the solar system; $\dot{X} \equiv dX/dt$.

$|V_{diurnal}| \leq 0.4654$ km/s

$|V_{orbital}| \leq 30$ km/s



Light-time Correction

Heliocentric time = Earth's time + light-time correction

light-time correction = $0^{d}.0057756$ ($X \cos \alpha \cos \delta + Y \sin \alpha \cos \delta + Z \sin \delta$)

where X, Y and Z are the equatorial rectangular coordinates of the Sun

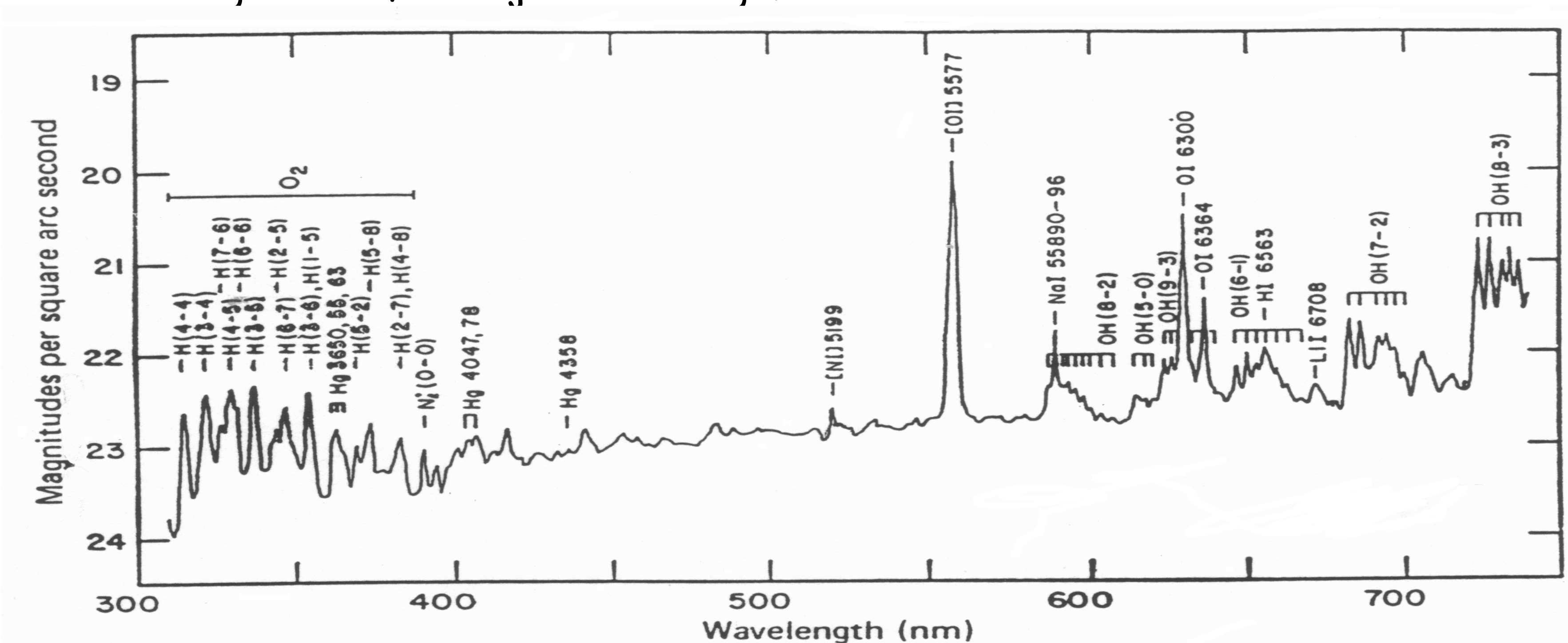
$0^{d}.0057756$ = 1 au/c = 8.317 mn (c = 299792.5 km/s)

Telluric lines

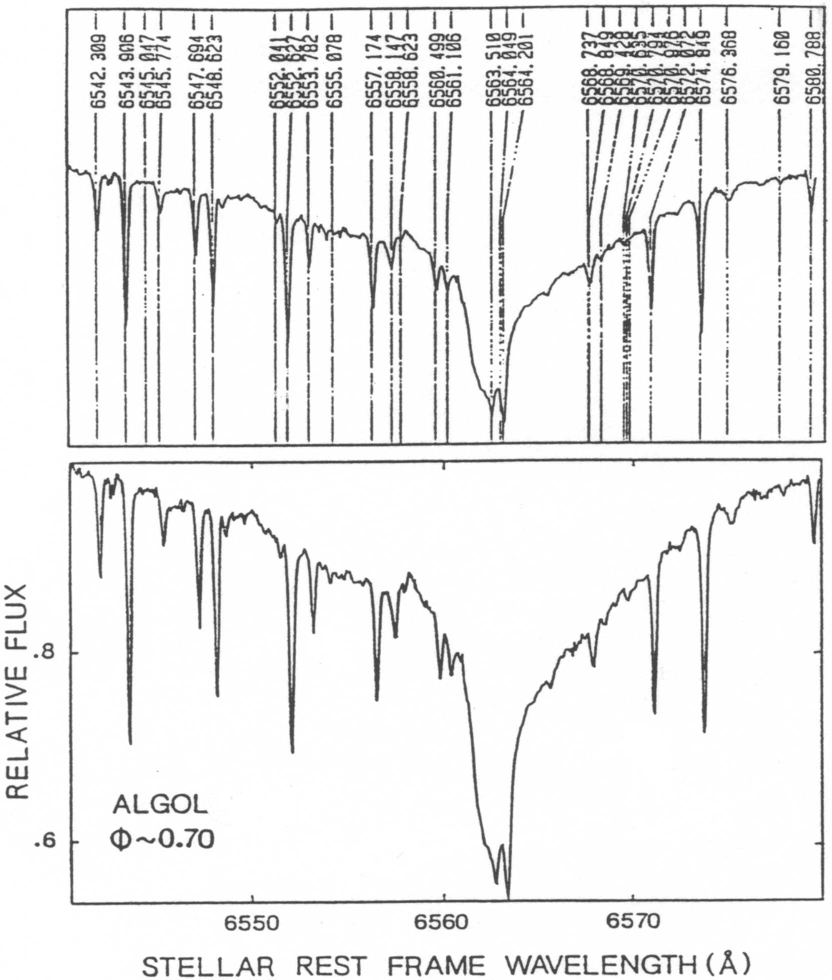
The *black sky* has a spectrum due to the:

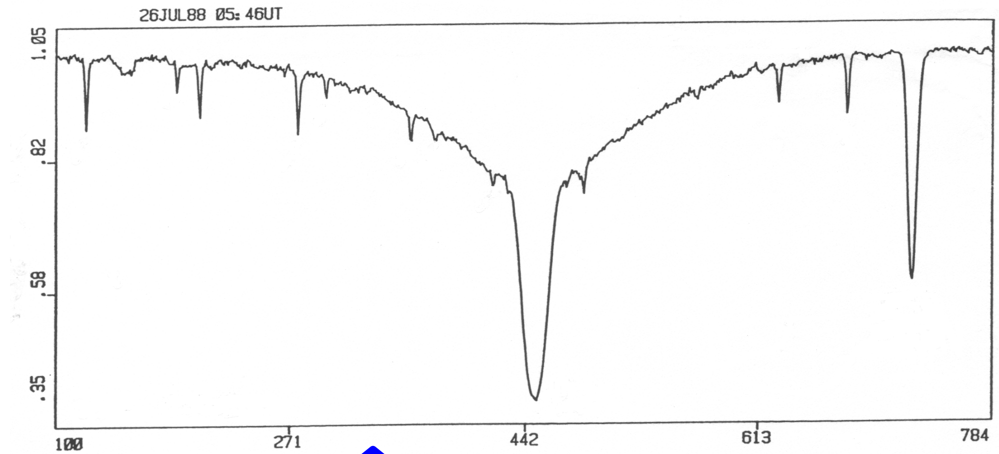
- earth atmosphere (natural and artificial light)
- other sources, mainly the diffused solar spectrum (moon, zodiacal light)

Can be neglected for objects having V < 13

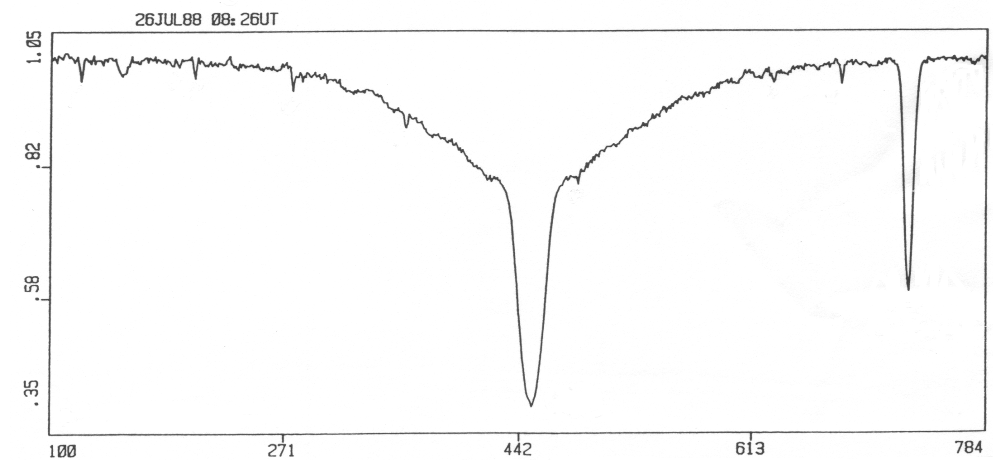


Water telluric lines



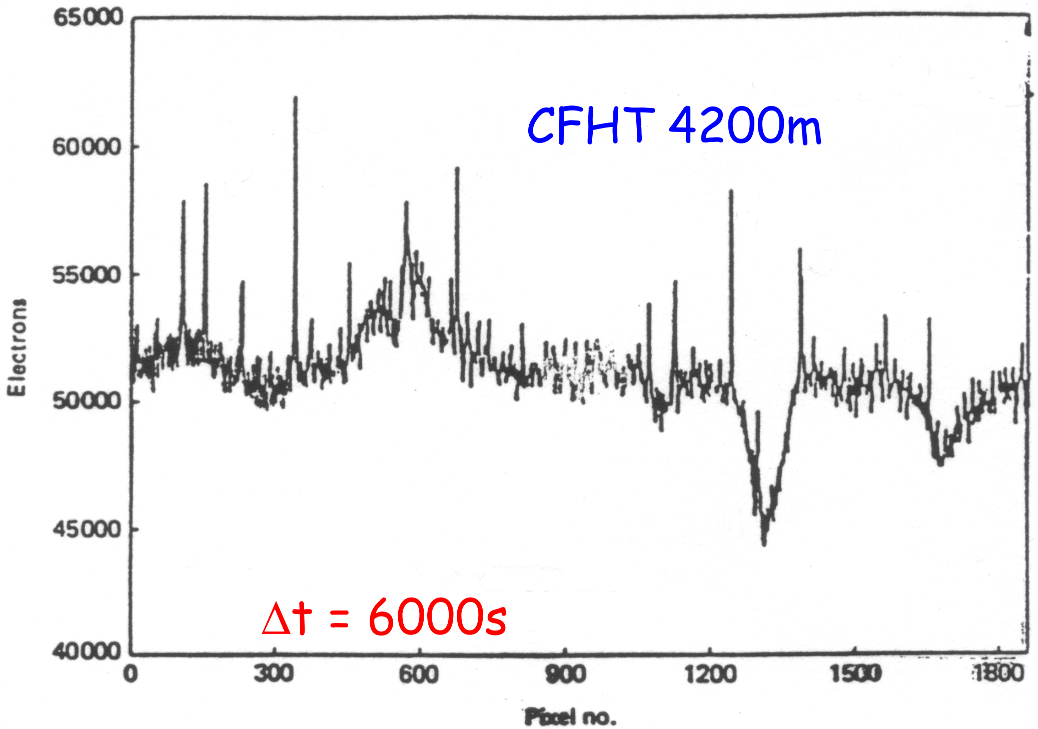


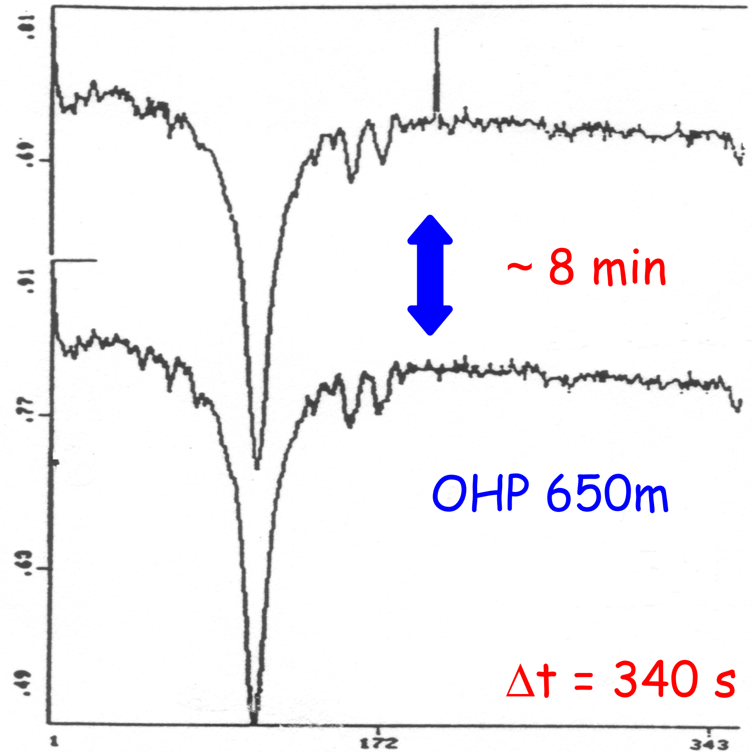
Δ t = 3h



Cosmic rays

- mainly due to H & He nuclei, but also e, μ, π...
- better to make a few short exposures rather than a unique long one





Natural broadening

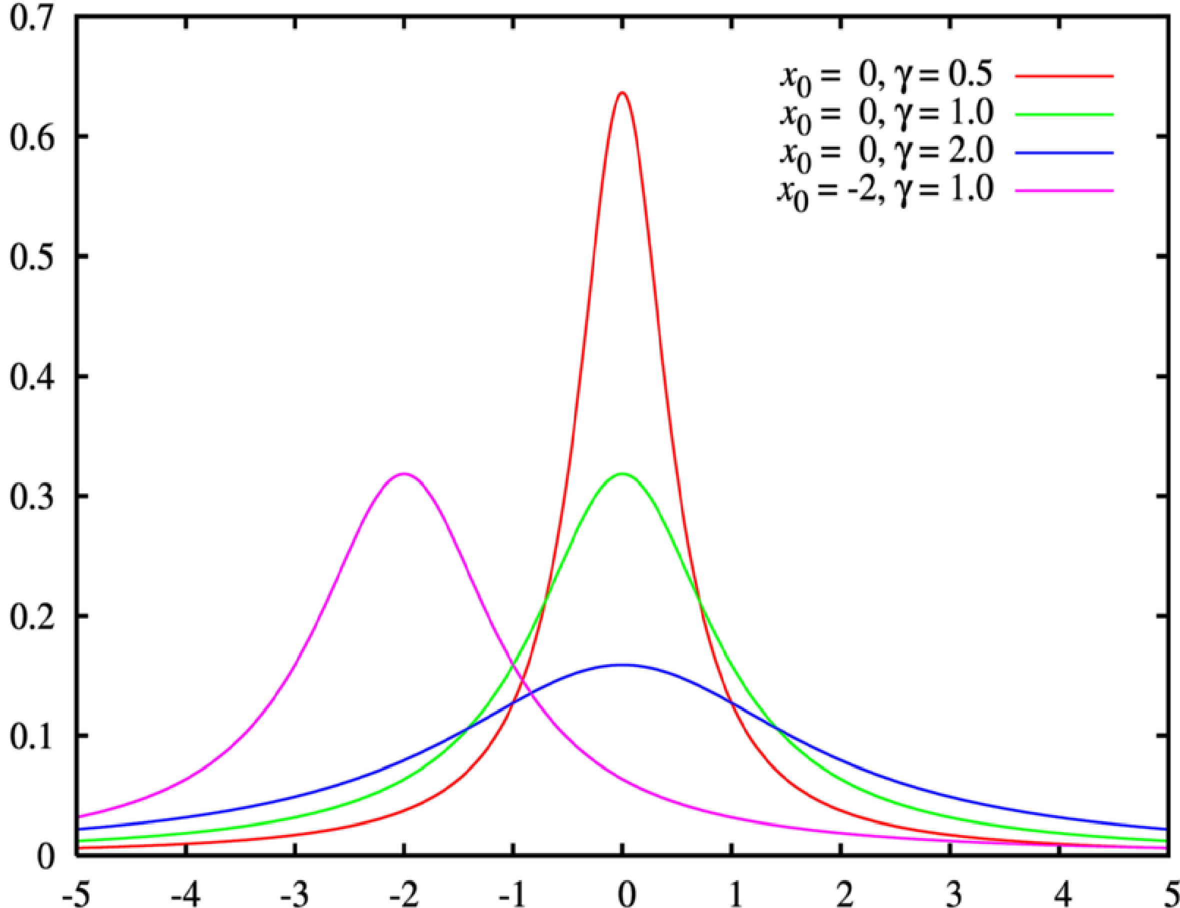
Results from the intrinsic width of the energy levels

$$\varphi(\nu) = \frac{\gamma}{\pi} \frac{1}{\gamma^2 + (\nu - \nu_0)^2}$$

with γ :

physical process parameter

Characterized by a Lorentzian profile:



Pressure broadening

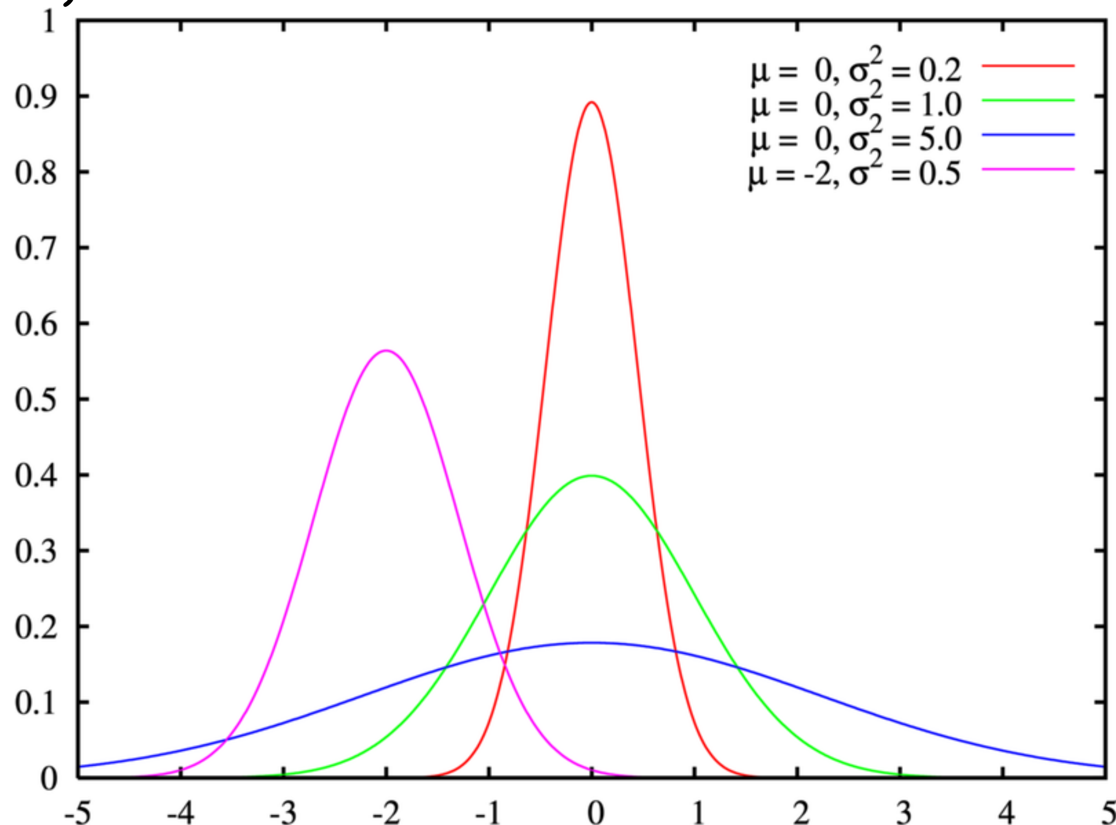
- Also called collision broadening
- Due to the perturbation of the orbitals by nearby atoms, ions, electrons...
- Orbitals also perturbed by electric field of ionized particles
- Collision with H atom modelled by linear Stark effect: energy levels splitting due to electric field
- Leads to a Lorentzian profile

Doppler broadening

Consequence of thermal motion inducing a Maxwellian distribution of velocities of atoms in the gas (LTE):

$$\varphi(\nu) = \sqrt{\frac{mc^2}{2\pi kT \nu_0^2}} \exp\left(\frac{mc^2}{2kT} \frac{(\nu - \nu_0)^2}{\nu_0^2} \right)$$

Characterized by a Gaussian profile:



Total broadening

Generally: $\gamma_N \ll \gamma_D < \gamma_P$

The total profile is obtained through the convolution of the different process:

$G_1 * G_2 = G_{tot}$ with $W_{tot} = \sqrt{W_1^2 + W_2^2}$

$L_1 * L_2 = L_{tot}$ with $W_{tot} = W_1 + W_2$

$L_1 * G_2 =$ Voigt profile, with $W_{tot} = f(W_1, W_2)$

The Voigt profile

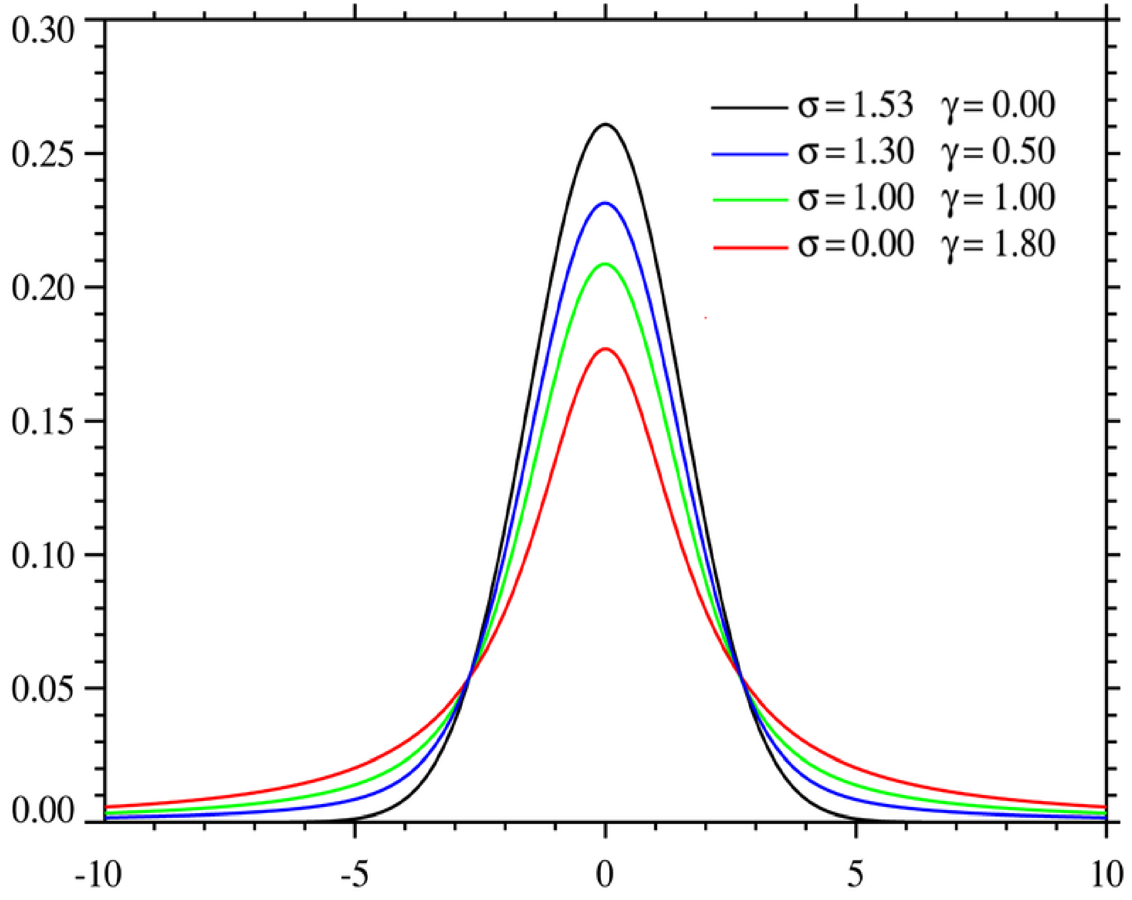
$$\varphi(\nu)=\sqrt{\frac{mc^2}{2\pi kT\nu_0^2}}\;H(a,u)$$

with:

$$H(a,u)=\frac{a}{\pi}\frac{\int_{-\infty}^{+\infty}\exp(-u')^2}{a^2+(u-u')^2}du'$$

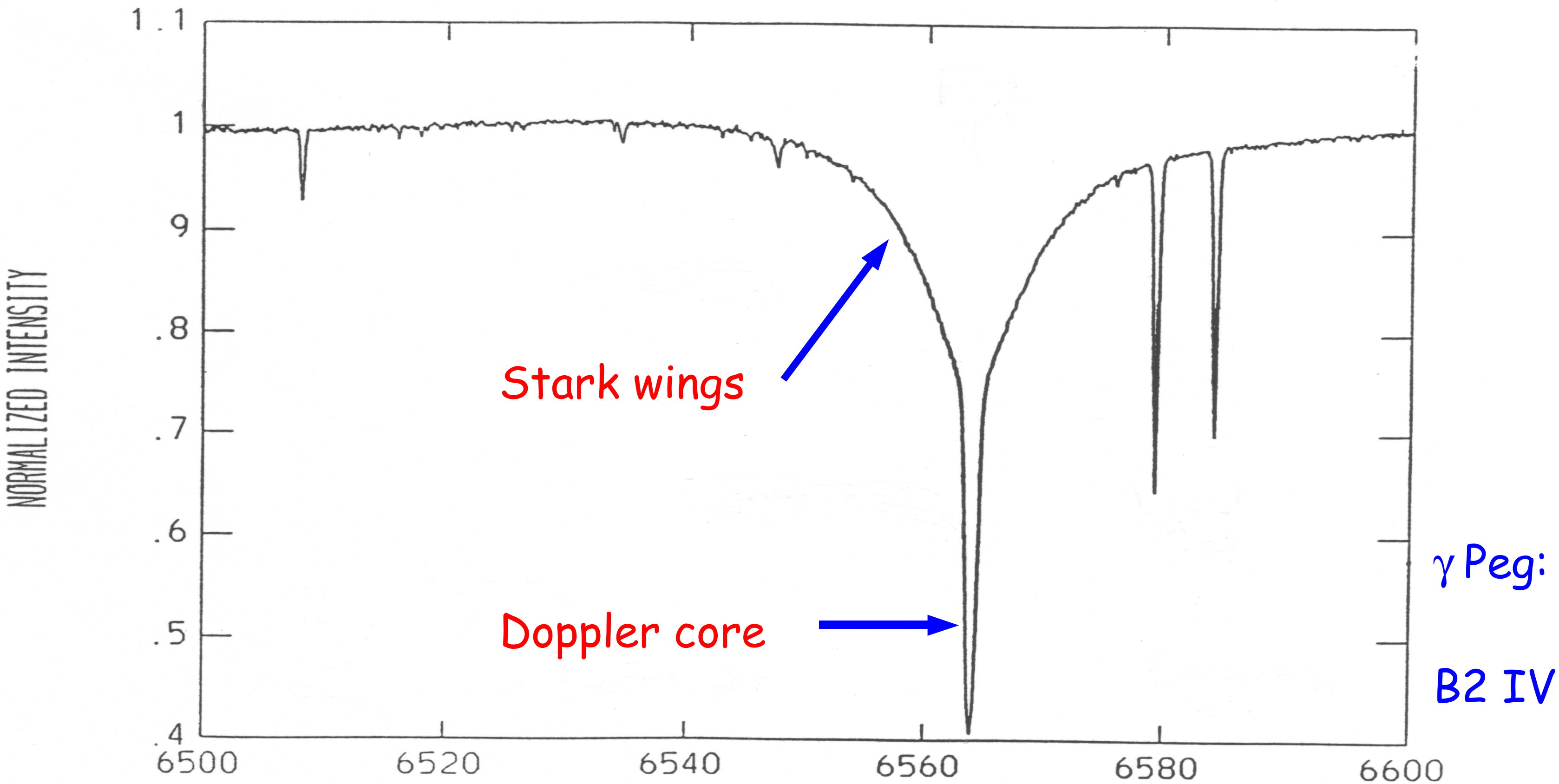
$$u=\sqrt{\frac{mc^2}{2kT}}\;\frac{(\nu-\nu_0)^2}{\nu_0{}^2}$$

$$a=\gamma\sqrt{\frac{mc^2}{2kT\nu_0^2}}$$

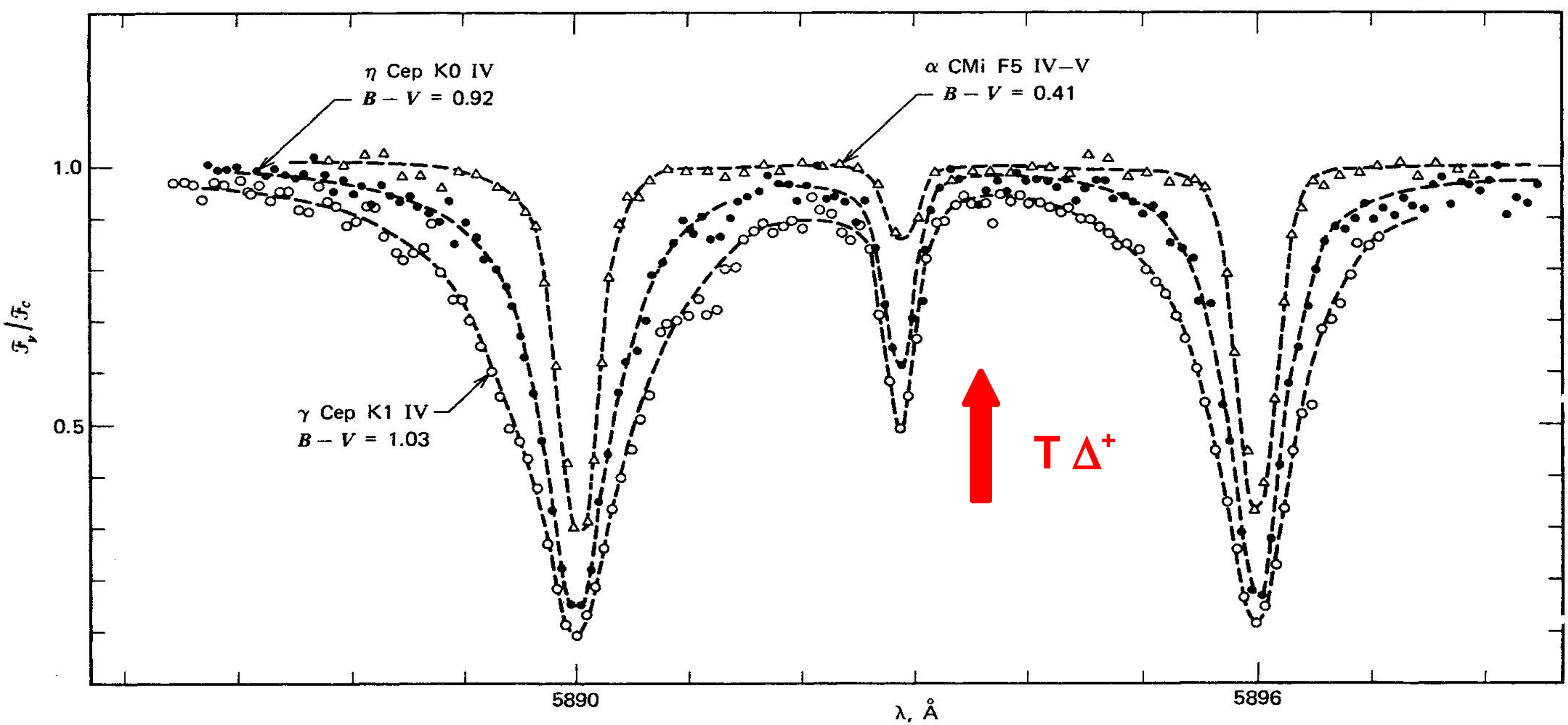


The Voigt profile

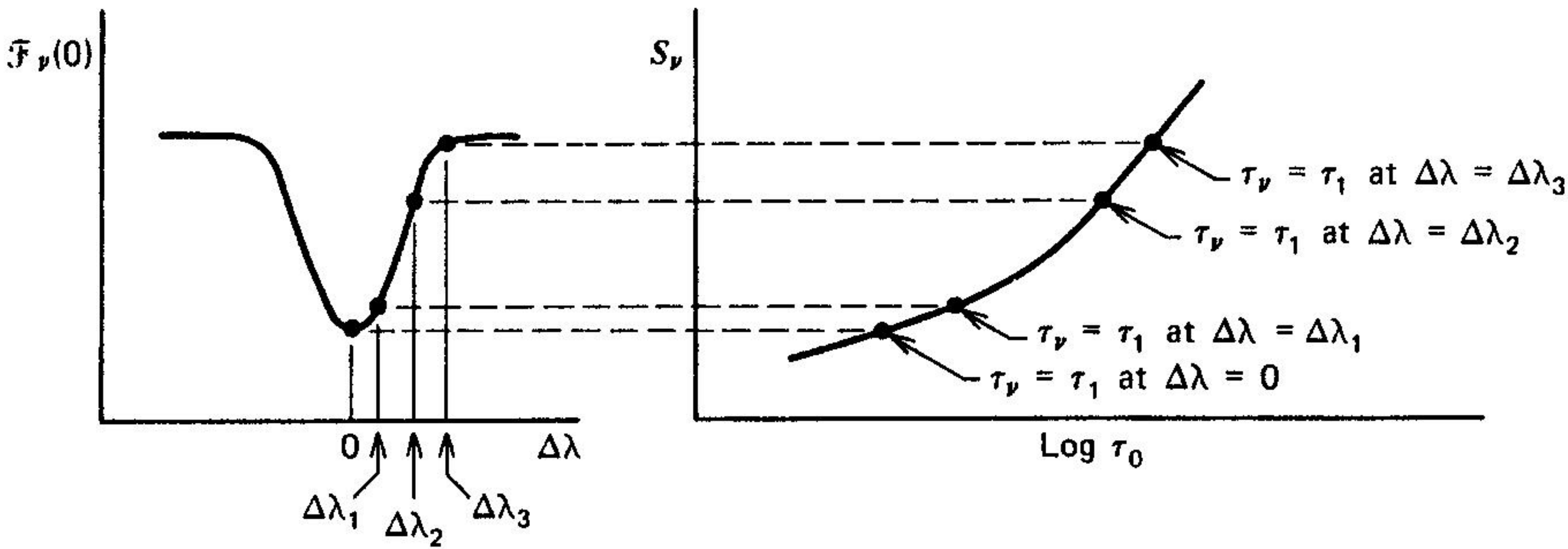
Useful approximation: $H(a,u) \approx e^{-u^2} + \frac{a}{\sqrt{\pi}\,u^2}$



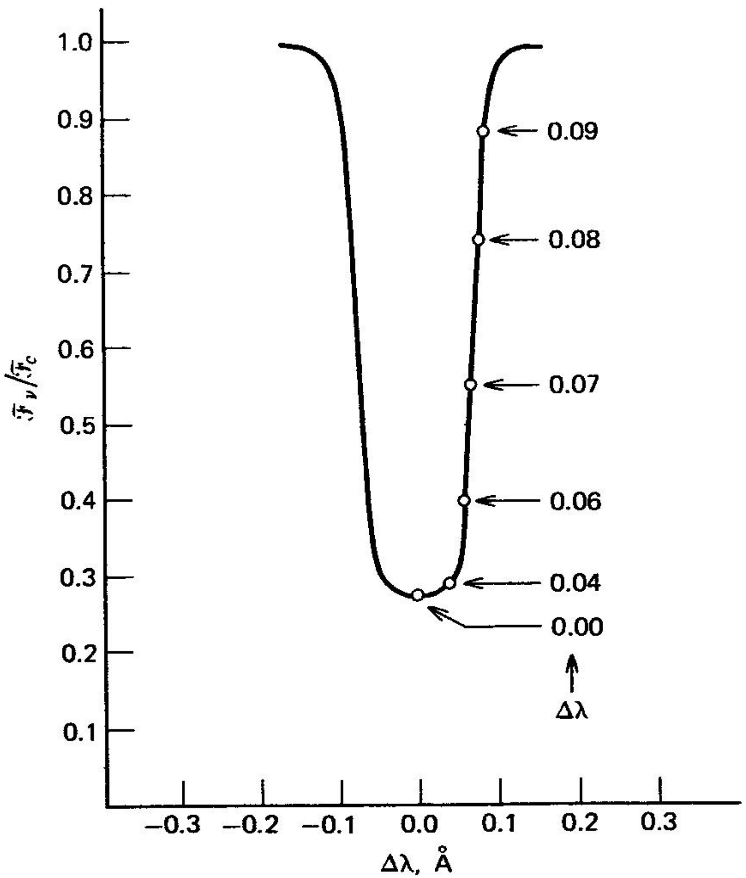
Line flux variations

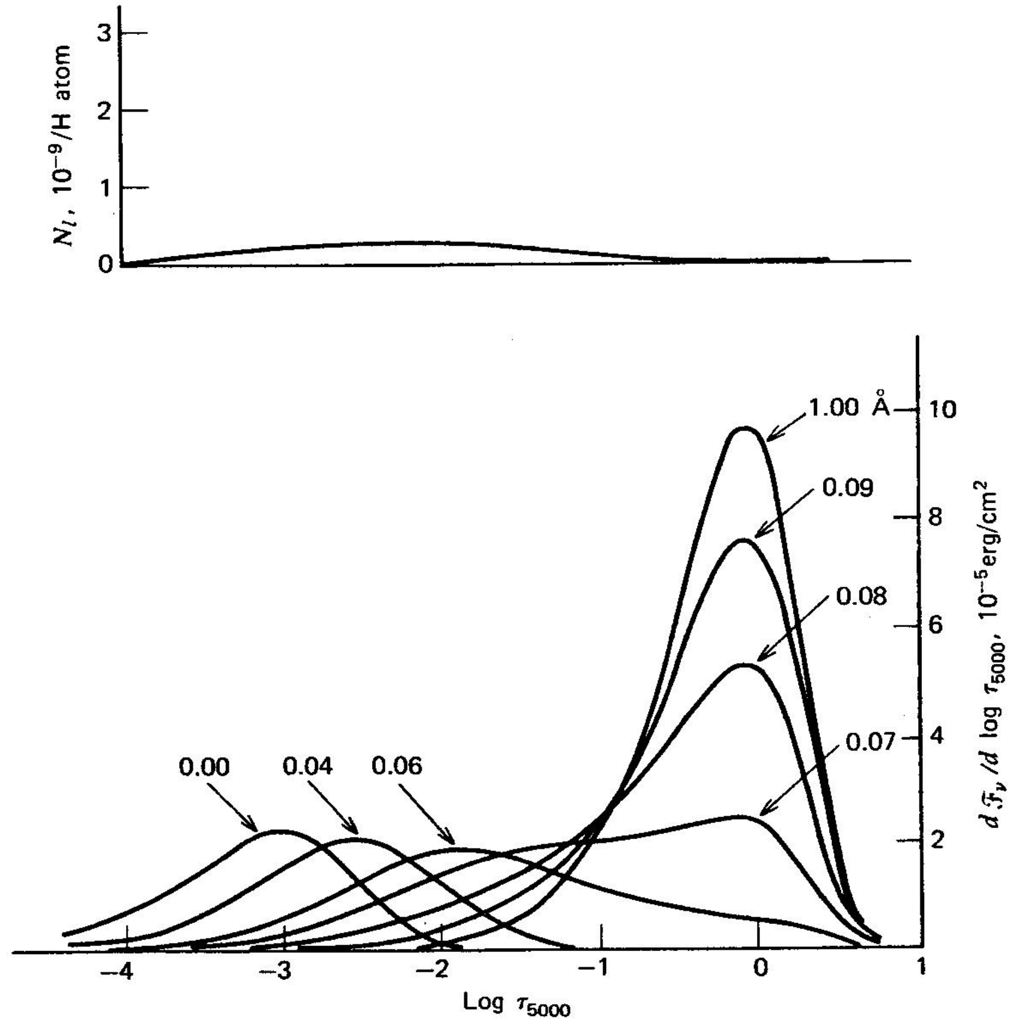


Line forming region

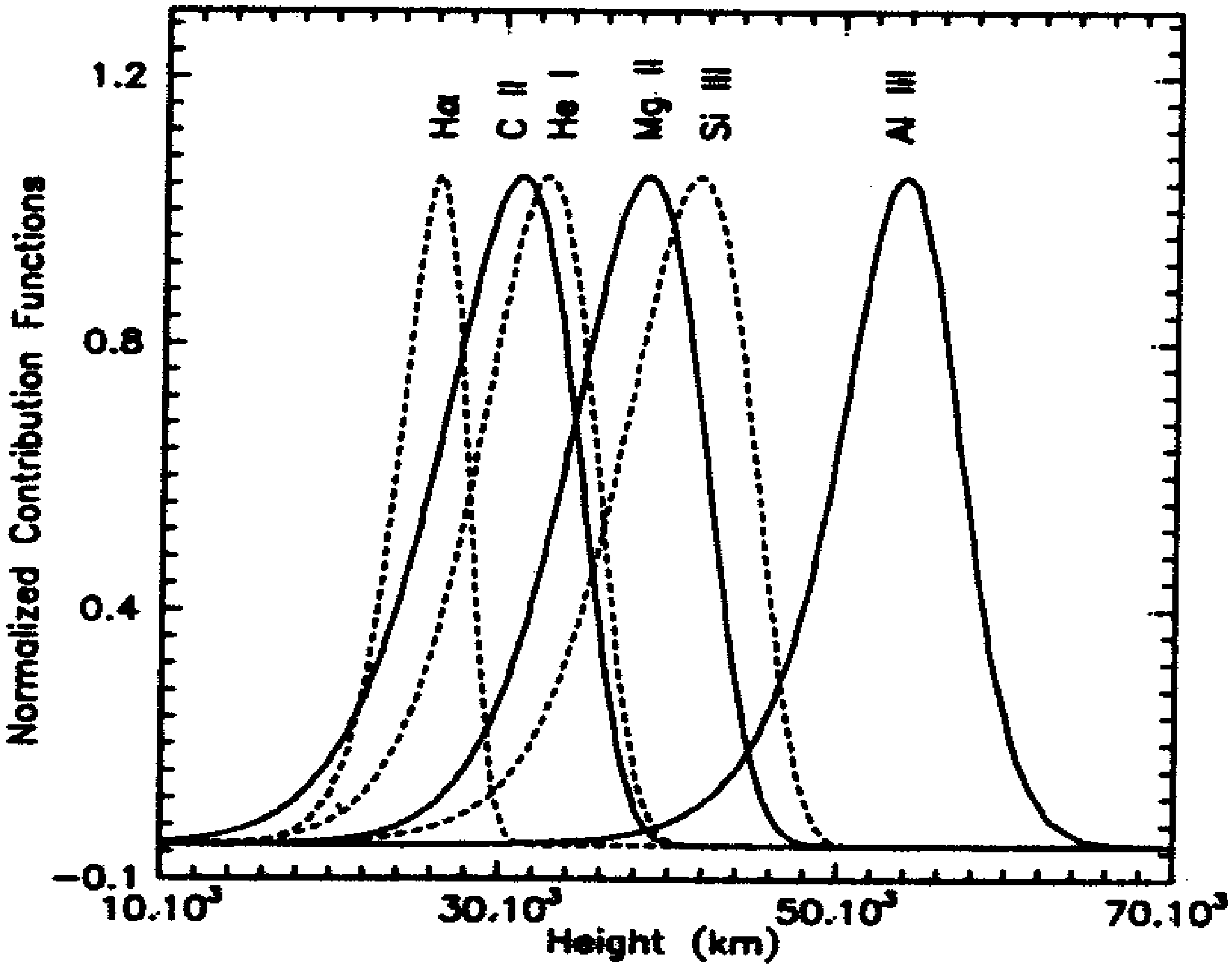


Contribution function

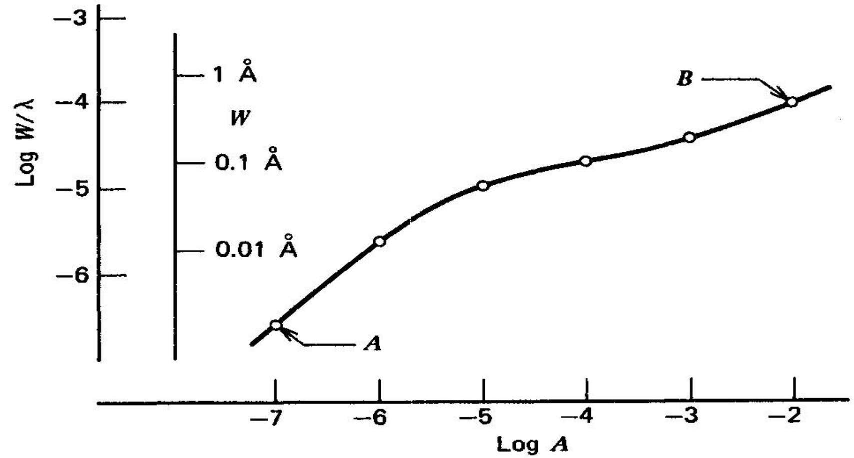




Contribution function



Abundances



Weak lines: Doppler core dominates:

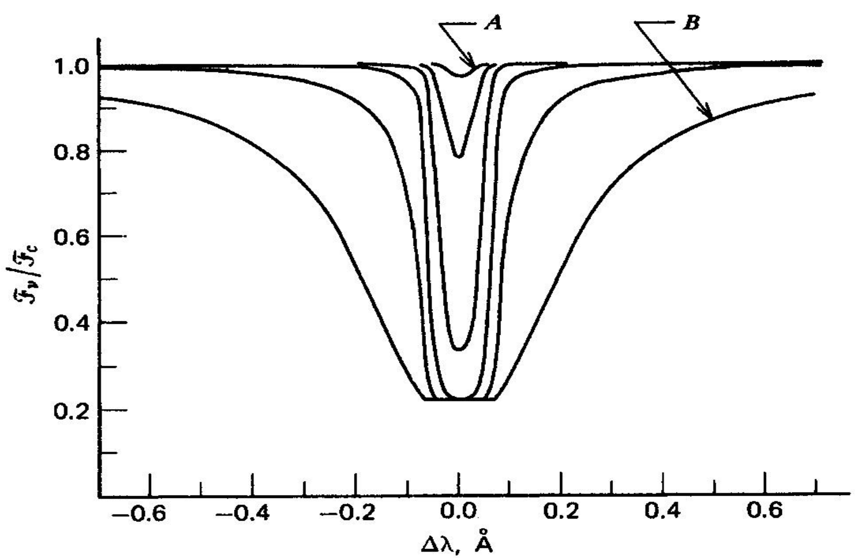
$$W \propto A$$

Saturated lines: asymptotic growth:

$$W = f(A)$$

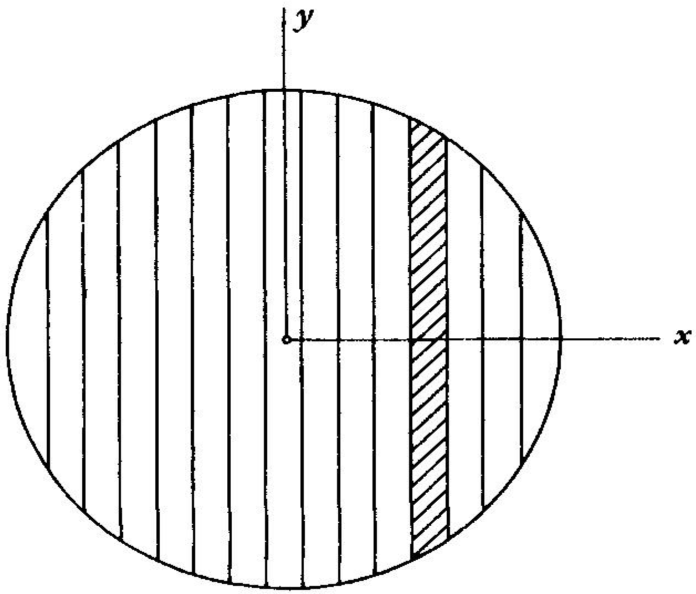
In the wings:

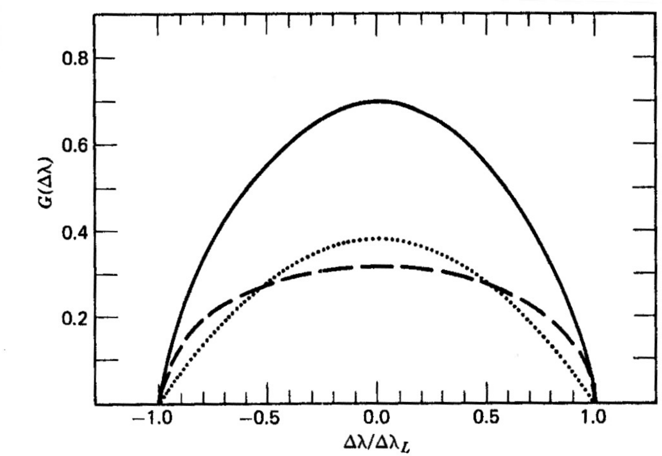
$$W \propto \sqrt{A}$$



Rotation profile

Given by (no differential motion): $a(\lambda)=\frac{2}{\pi b}\sqrt{1-\left(\frac{\Delta\lambda}{b}\right)^2}$ with $b=\lambda_0\frac{v\sin i}{c}$

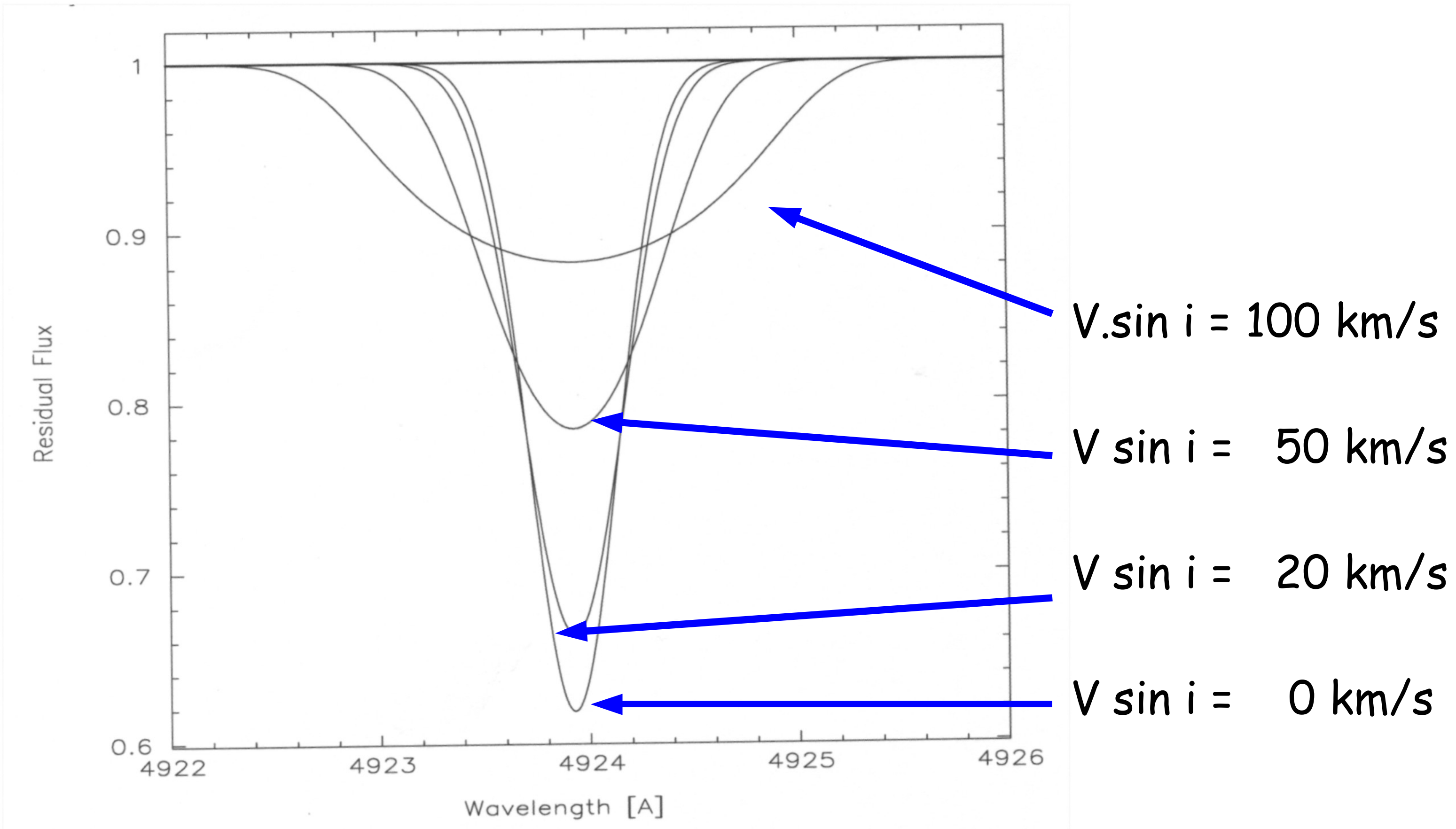




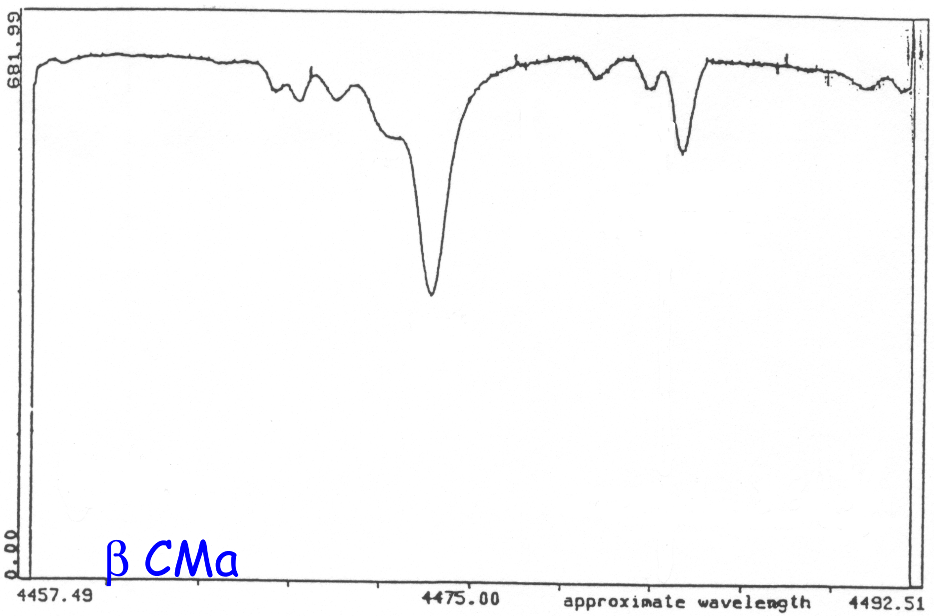
$$TF(a(\lambda))=A(\nu)=\int_{-\infty}^{+\infty}a(\lambda)\exp(2i\pi\nu\lambda)d\lambda=\frac{J_1(2\pi\nu b)}{\pi\nu b}$$

One has to find the zero of the Bessel function

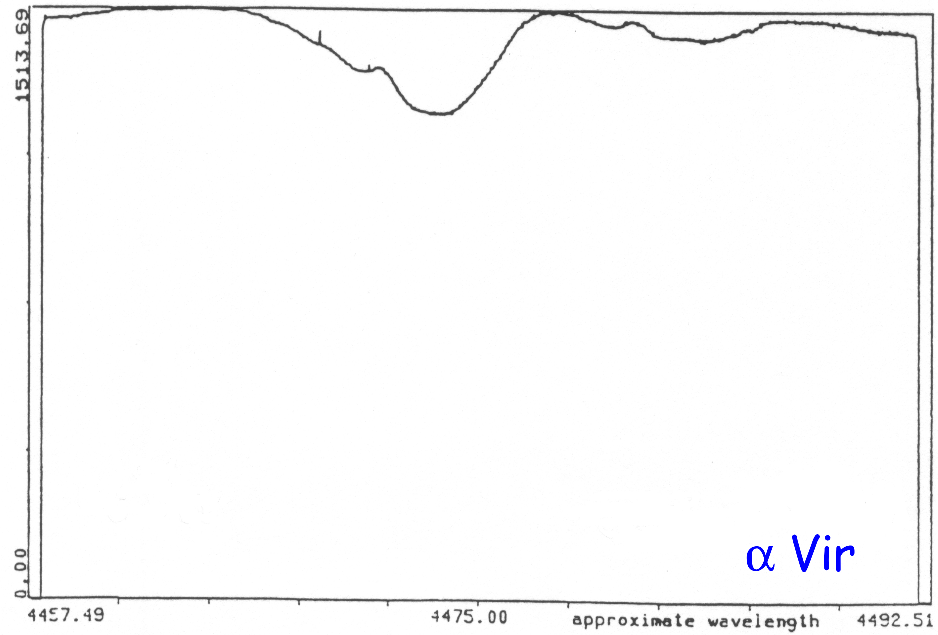
Rotational broadening



Rotation broadening

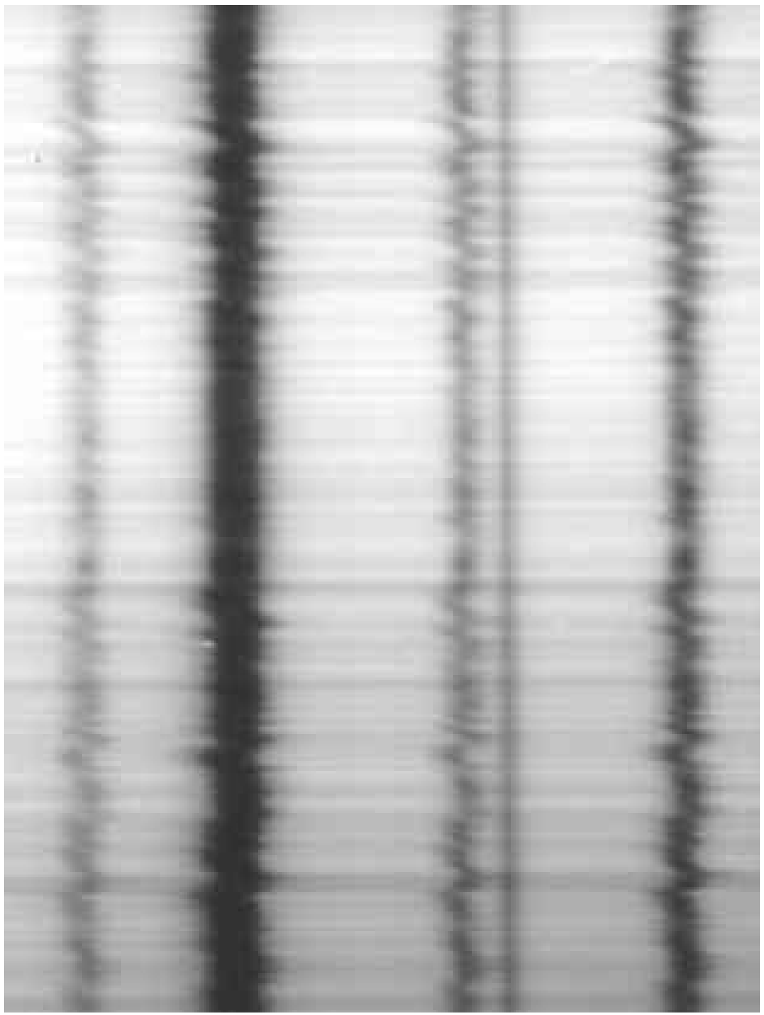


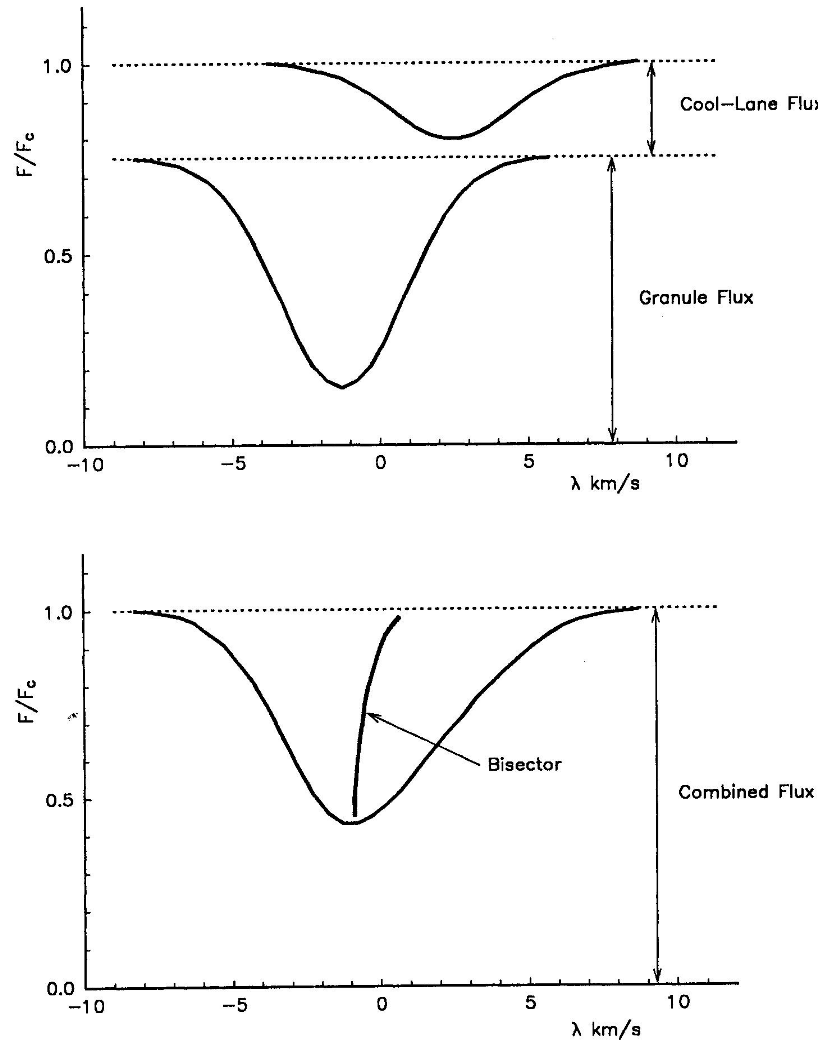
v sin i = 36 km/s



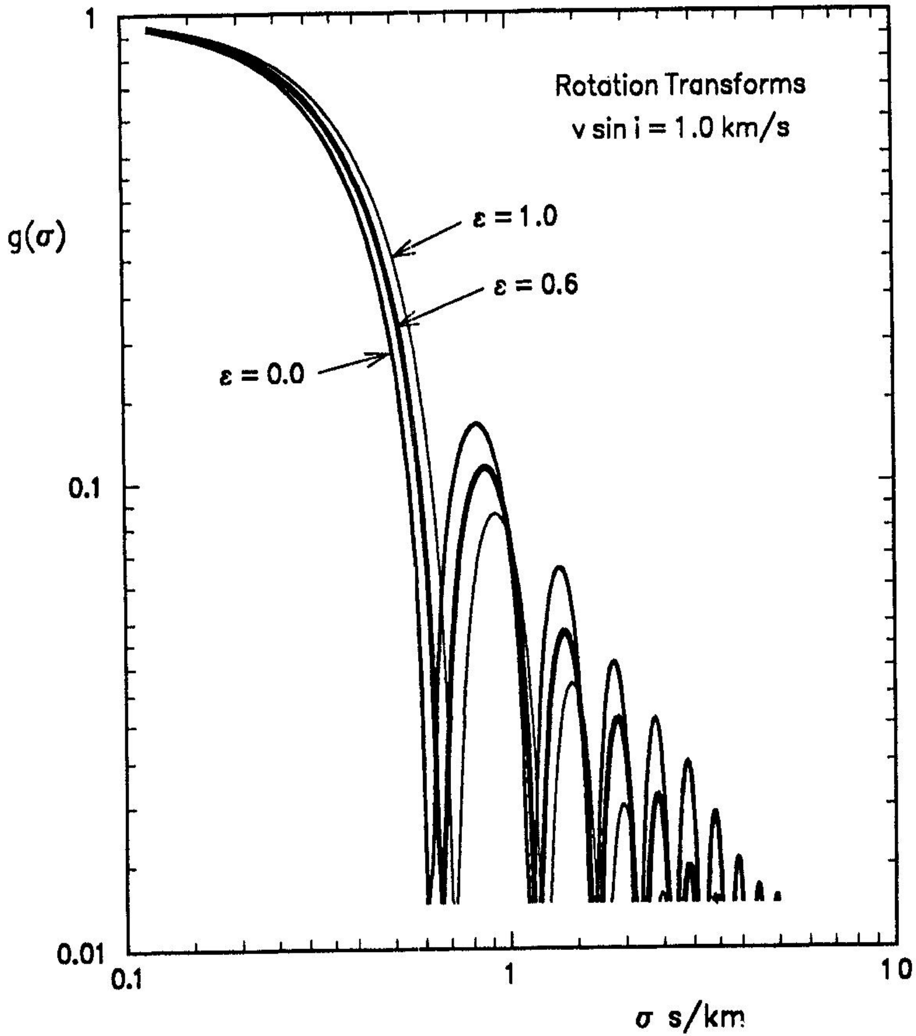
v sin i = 160 km/s

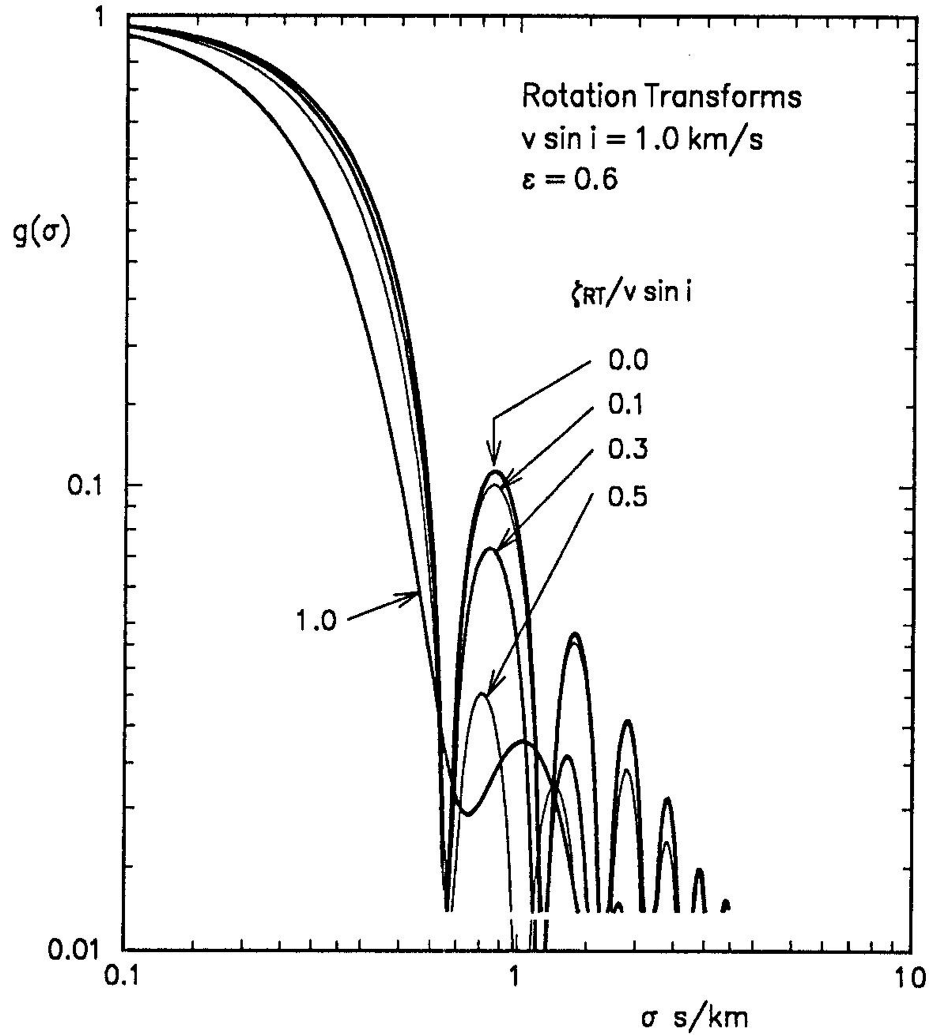
Microturbulence and convection





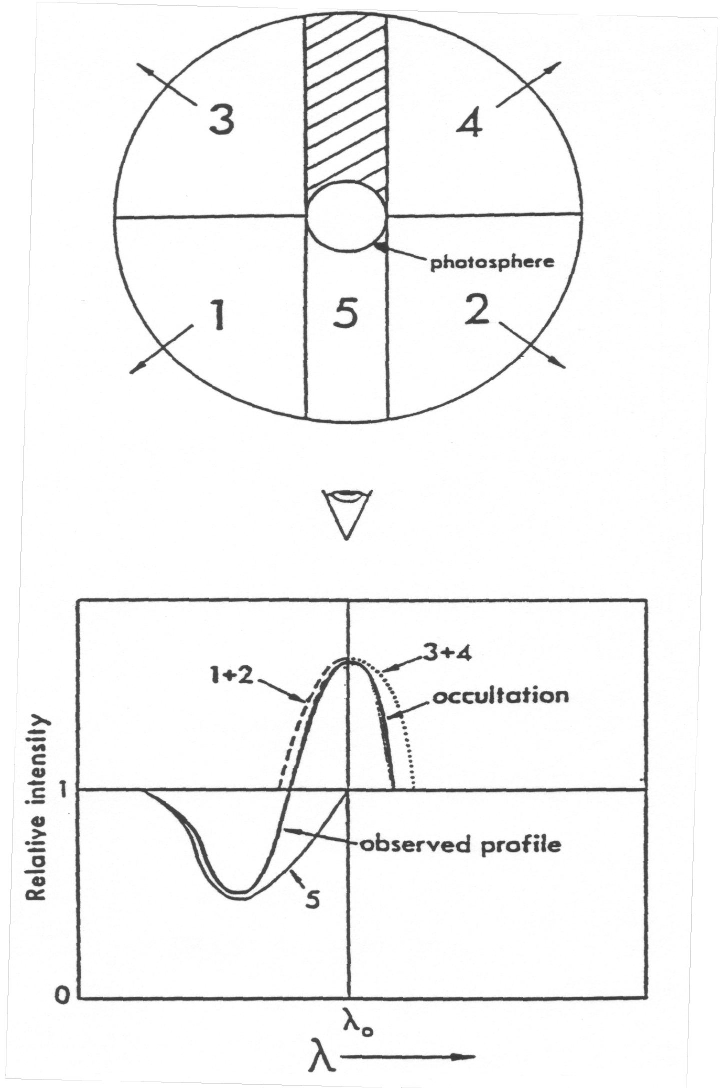
Measuring...


Rotation Transforms
v sin i = 1.0 km/s
ε = 1.0
ε = 0.6
ε = 0.0
g(σ)
1
0.1
0.01
0.1
1
10
σ s/km


Rotation Transforms
v sin i = 1.0 km/s
ε = 0.6
g(σ)
ζRT/v sin i
0.0
0.1
0.3
0.5
1.0
1
0.1
0.01
0.1
1
10
σ s/km

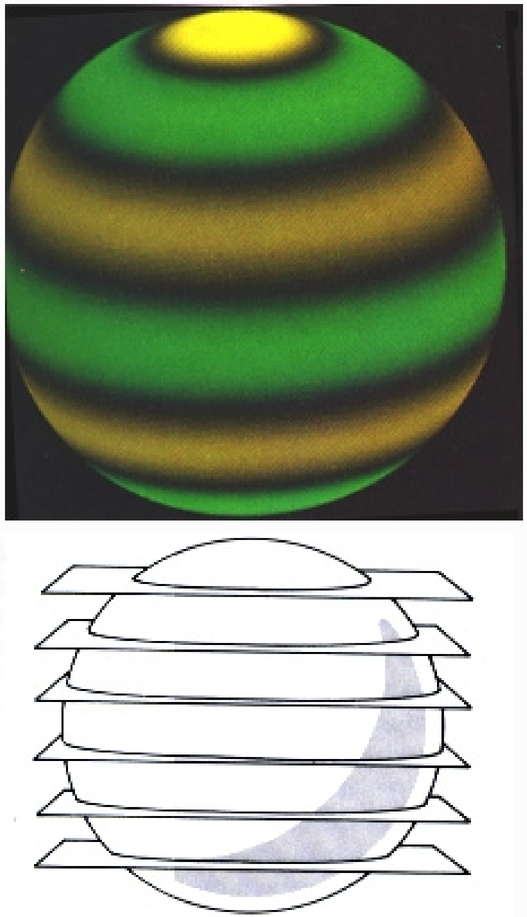
Large scale motions

P Cygni profile:

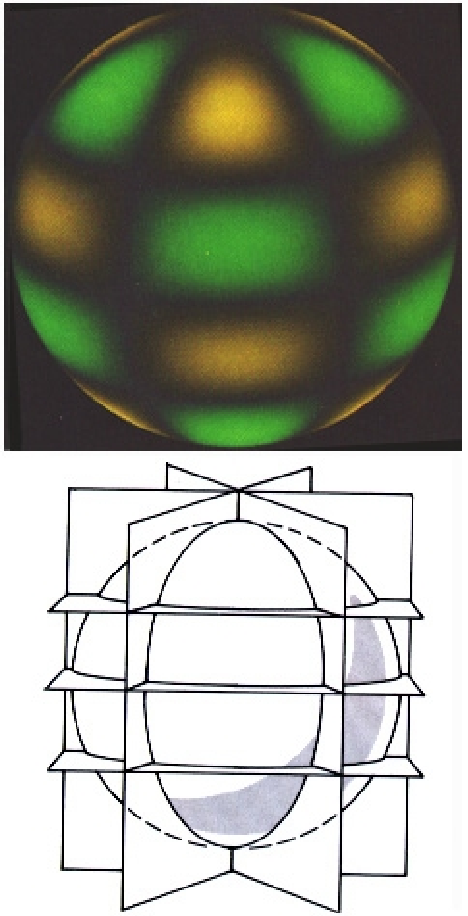


Non radial pulsations

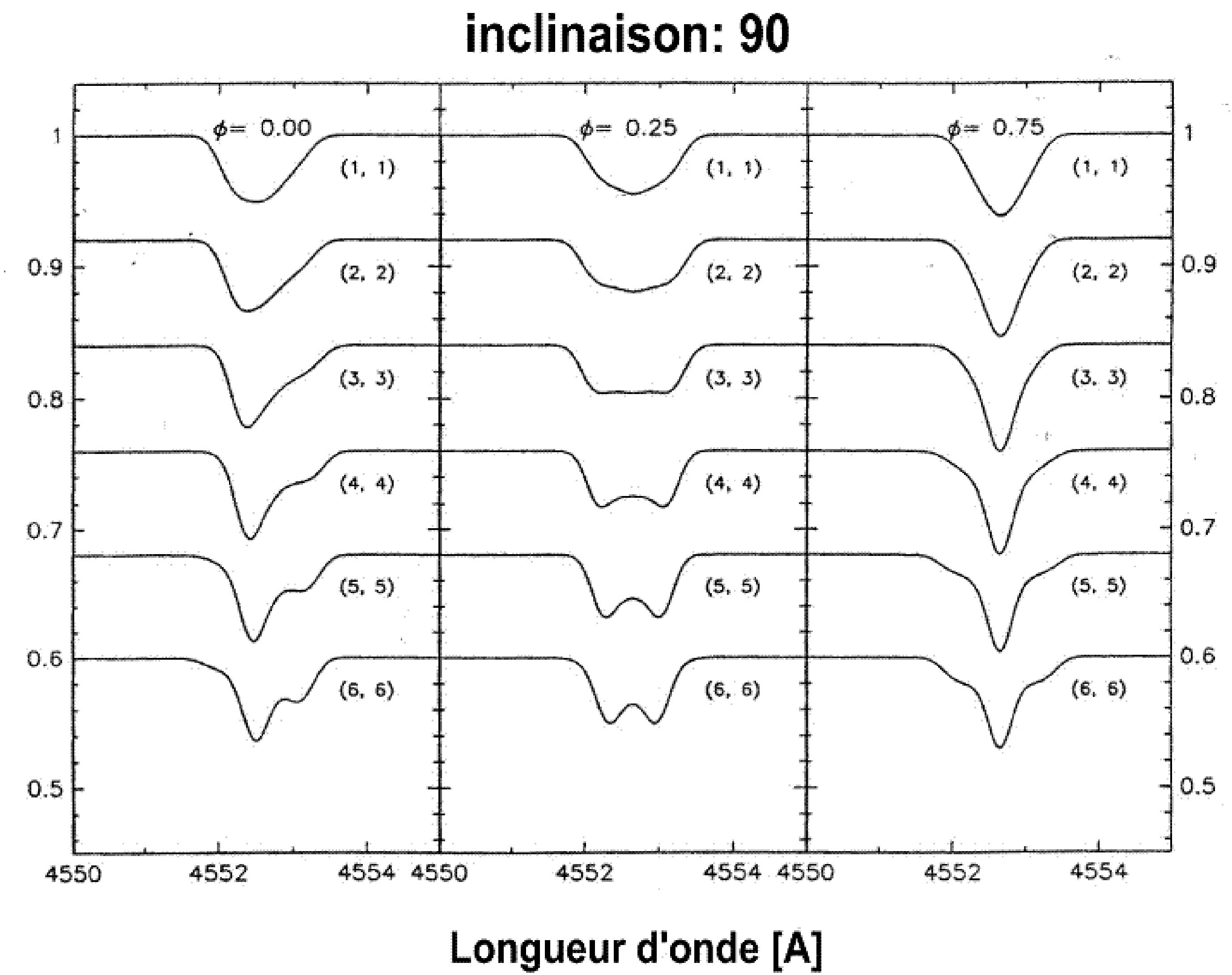
(l, m) = (6, 0)



(l, m) = (6, 4)

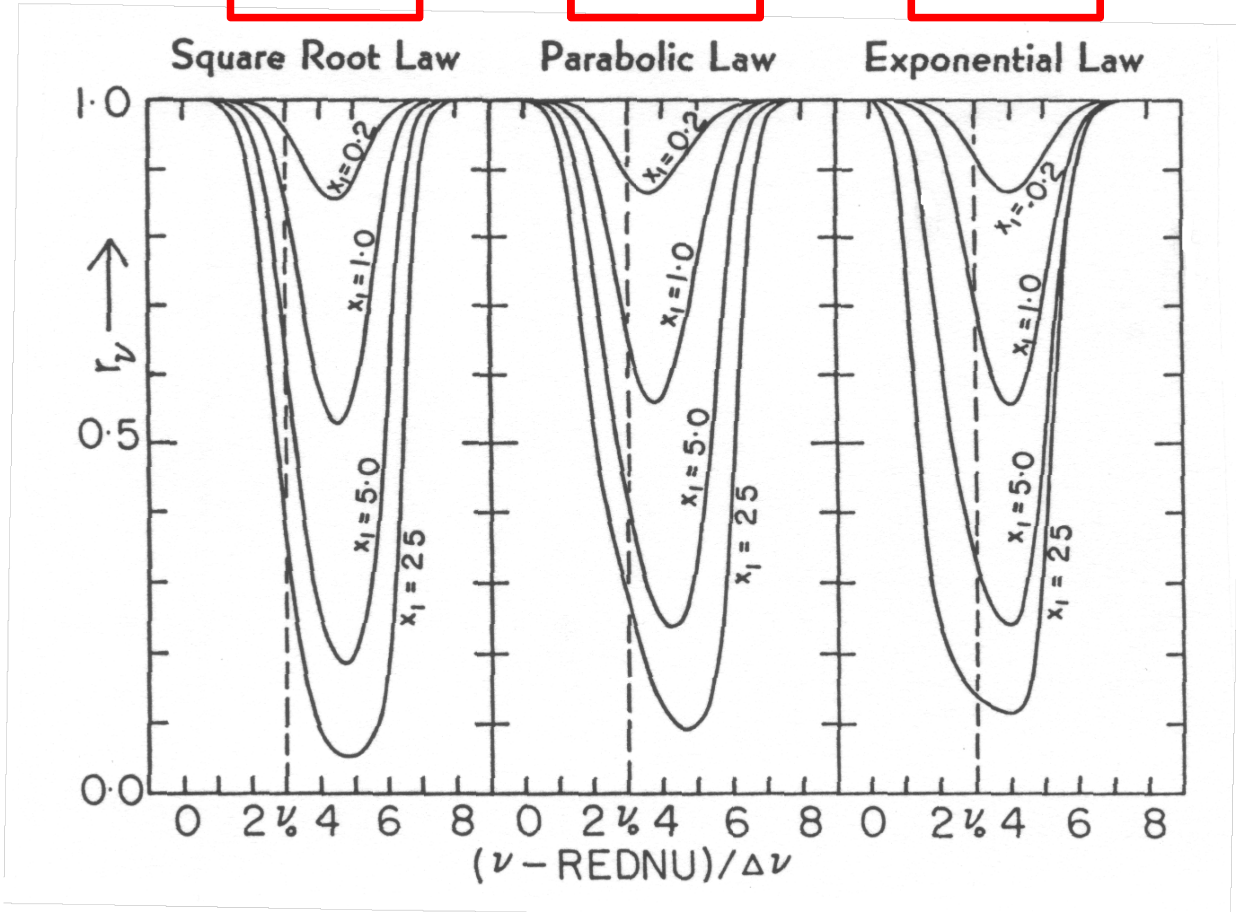


Non radial pulsations

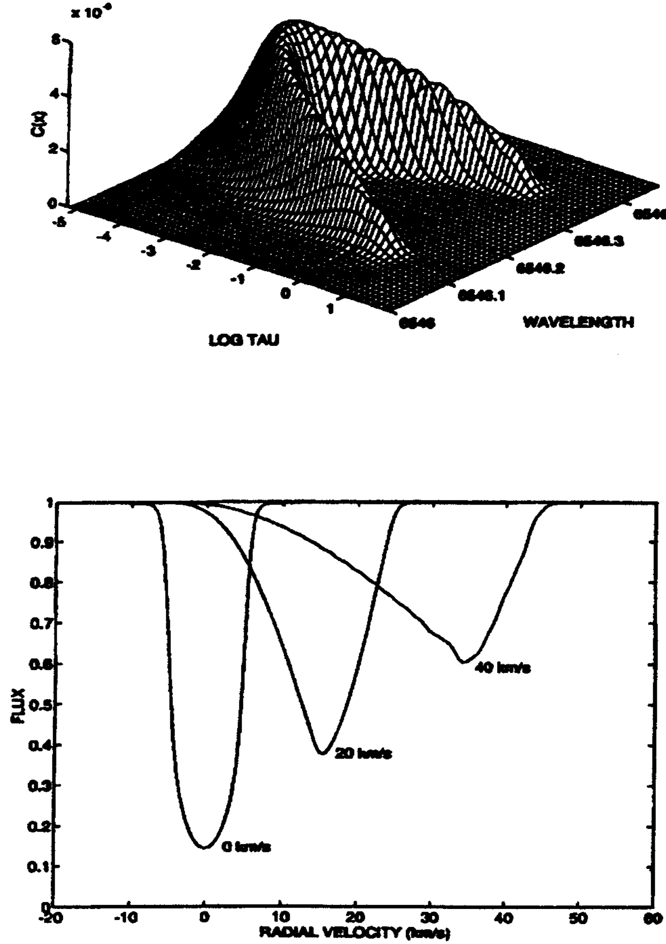


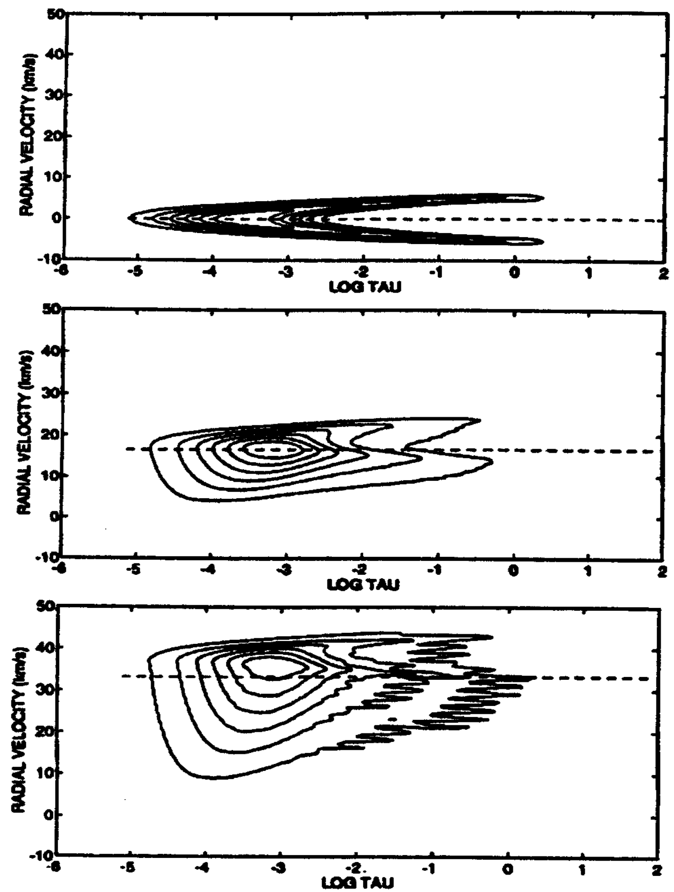
Wave propagation

$\propto \sqrt{\nu}$ $\propto \nu^2$ $\propto e^{\nu}$

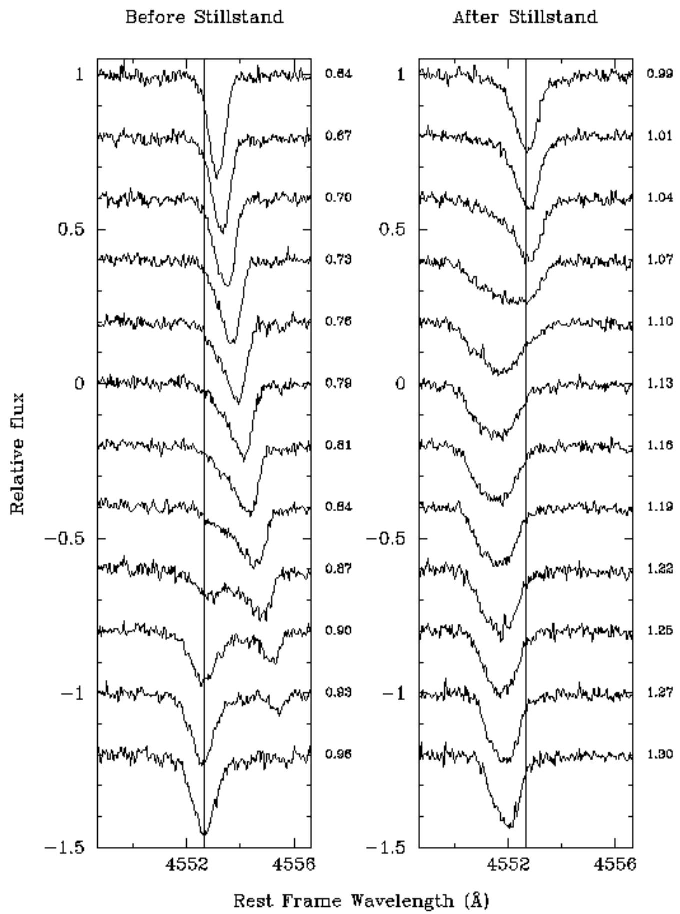


Velocity gradient

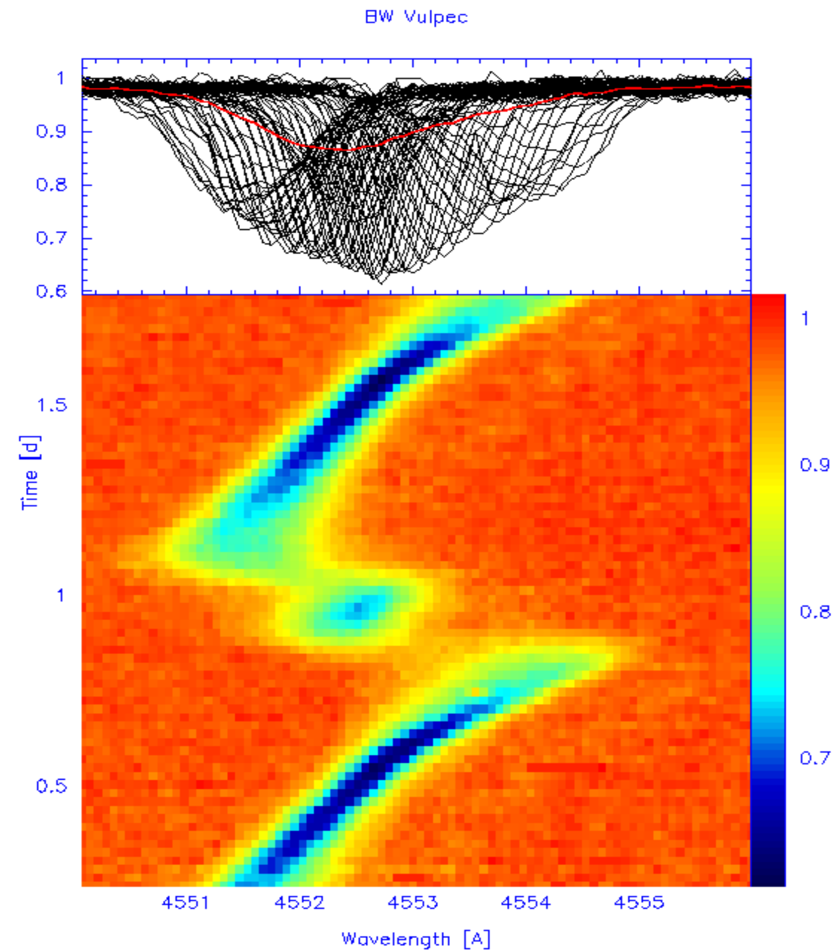




Shock waves

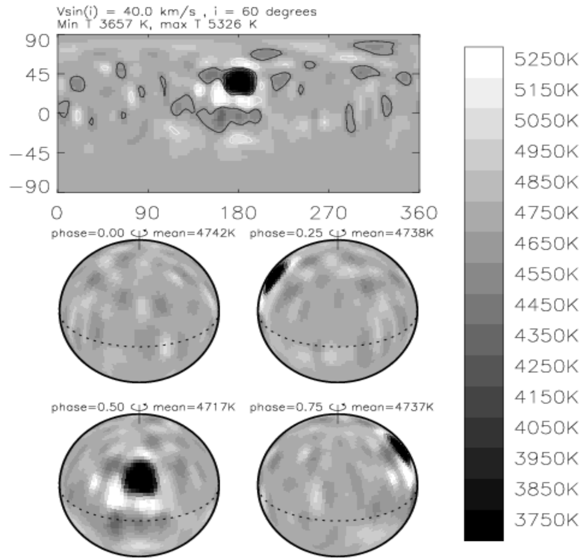


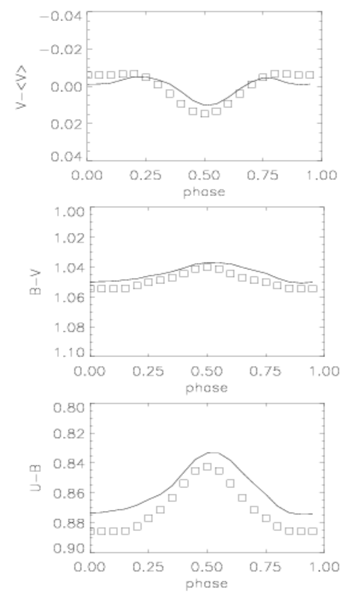
Before Stillstand
After Stillstand
Relative flux
1
0.5
0
−0.5
−1
−1.5
0.64
0.67
0.70
0.73
0.76
0.79
0.81
0.84
0.87
0.90
0.93
0.96
0.99
1.01
1.04
1.07
1.10
1.13
1.16
1.19
1.22
1.25
1.27
1.30
4552
4556
Rest Frame Wavelength (Å)

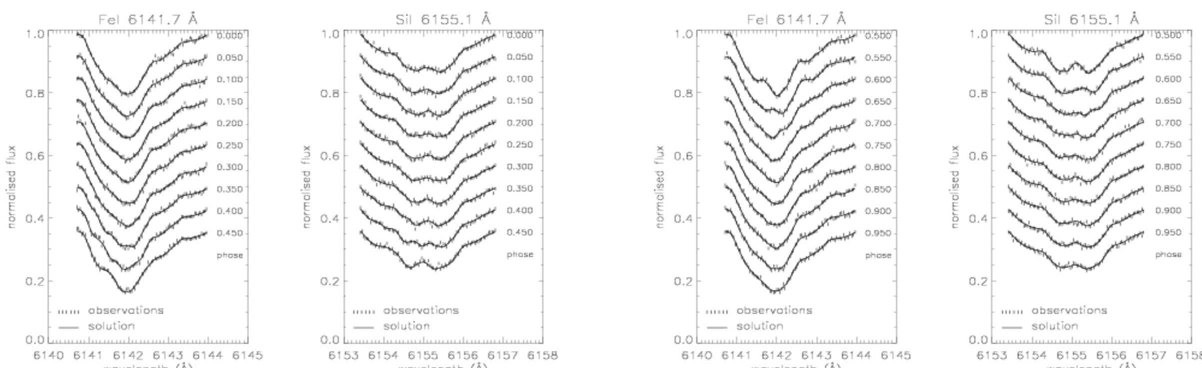


BW Vulpec
1
0.9
0.8
0.7
0.6
Time [d]
1.5
1
0.5
4551
4552
4553
4554
4555
Wavelength [A]
1
0.9
0.8
0.7

Doppler imaging







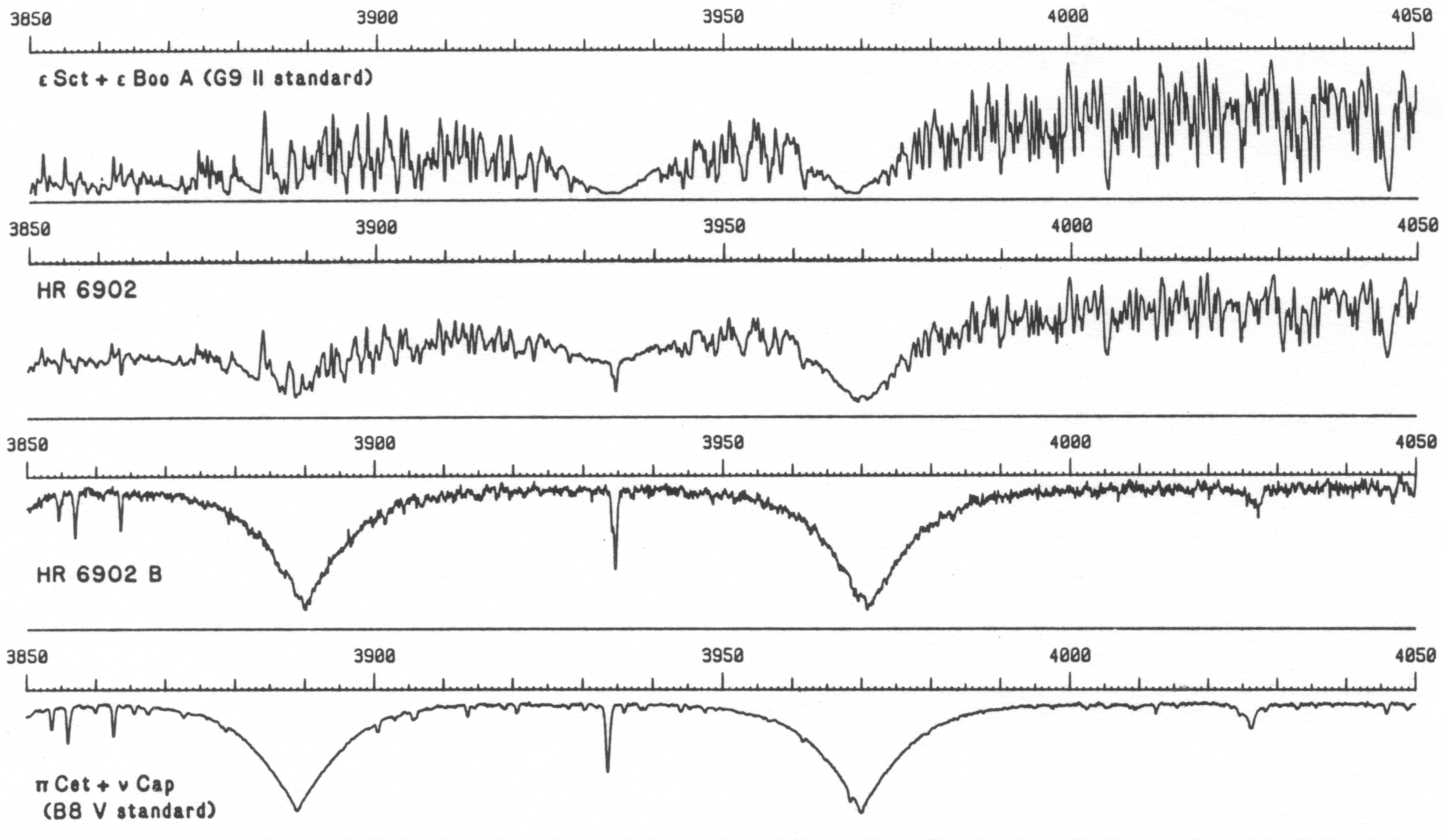
Composite spectra

Standard ~A

A + B

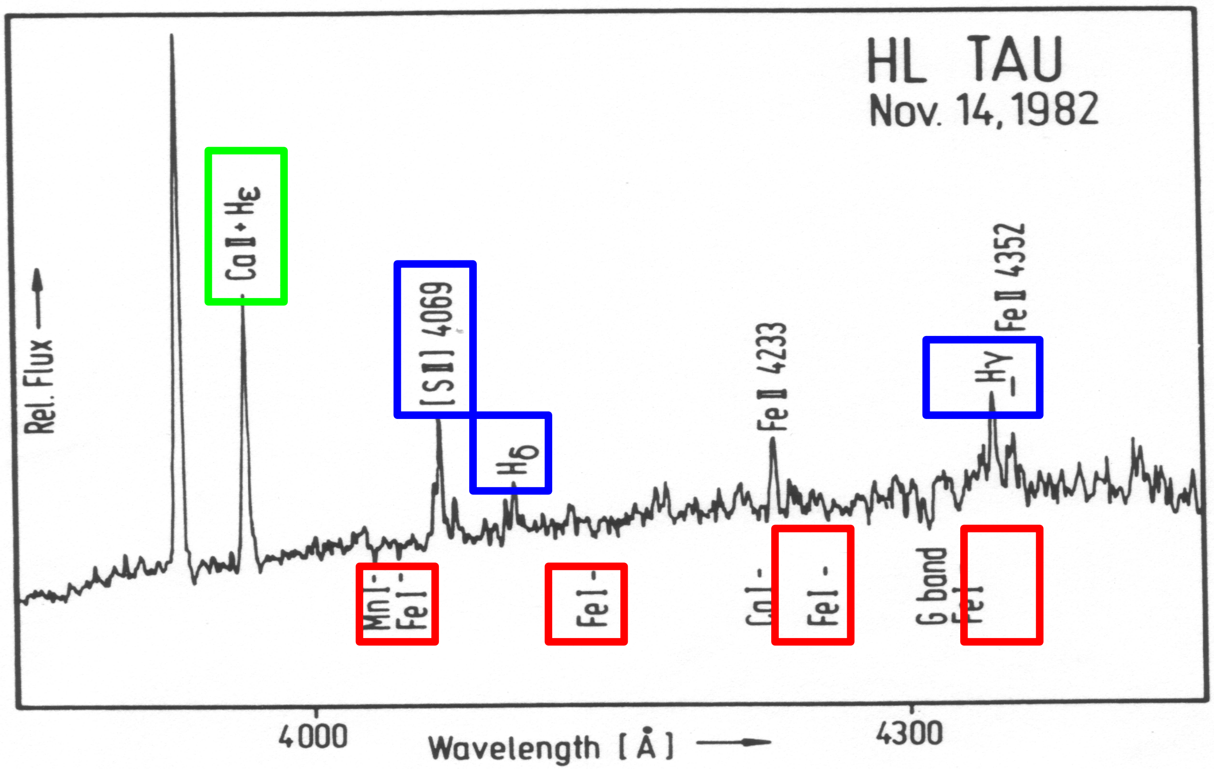
B

Standard ~ B



Composite spectra: PMS

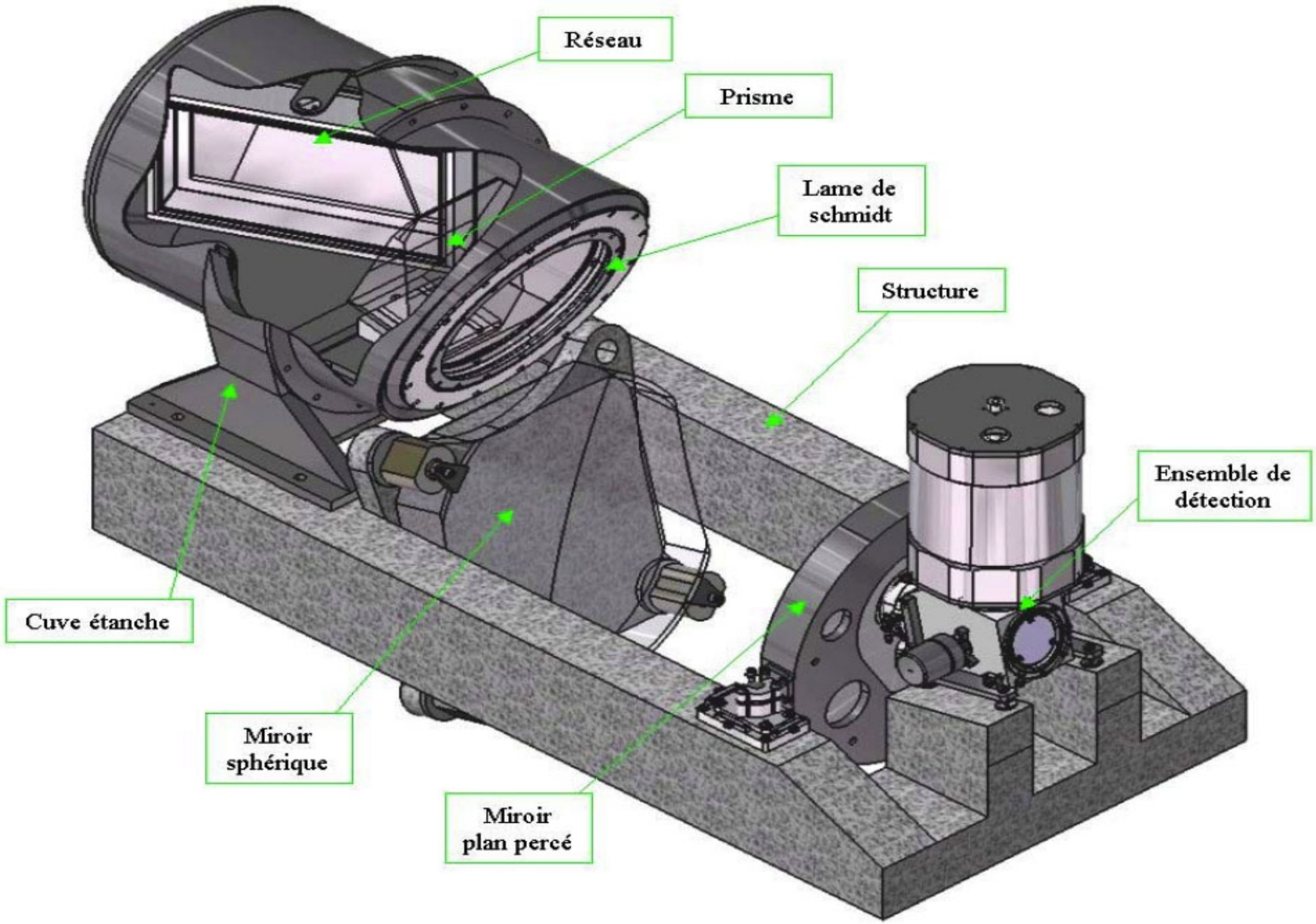
3 components: late type stars [abs]
dense chromosphere [em]
CS gas [em]



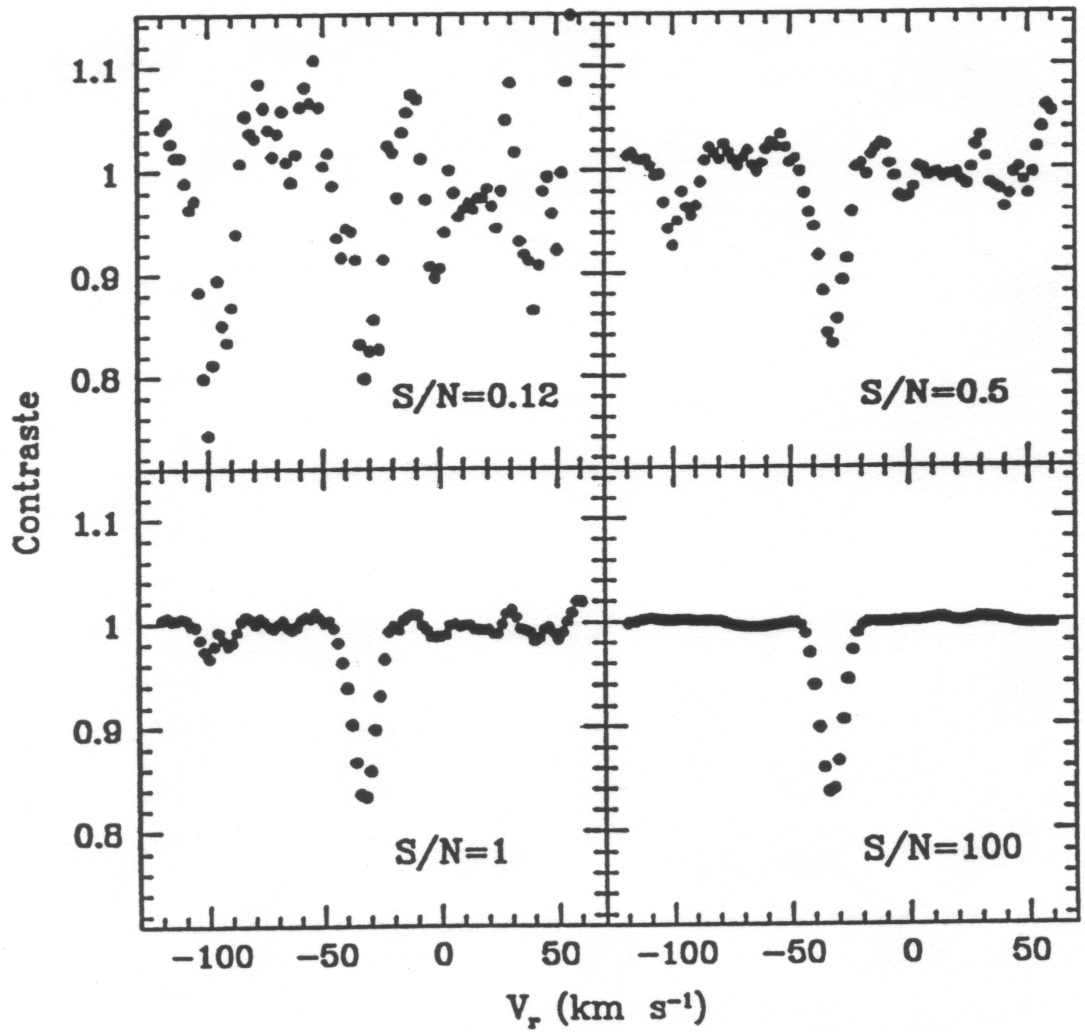
Spectrograph

télescope	spectrographe	dispersion croisée	$\Delta\lambda$ (nm)	R
		Hémisphère Nord		
CFH (3.6 m)	ESPADONS	prisme	620	50,000
Keck (10 m)	HIRES	réseau	200	40,000
Subaru (8 m)	HDS	réseau	<300	?
Hale (5 m)	fibre	prisme	300	40,000
WHT (4.2 m)	UES	prisme	240	50,000
Lick (3 m)	Hamilton	prisme	650	48,000
KPNO (4 m)	échelle	réseau	215	40,000
		Hémisphère Sud		
VLT (8 m)	UVES	réseau	170	40,000
Gemini (8 m)	HROS	prisme	?	?
AAT (3.9 m)	UCLES	prisme	230	50,000
NTT (3.5 m)	EMMI	réseau	300	60,000
ESO (3.6 m)	CASPEC	réseau	240	40,000
CTIO (4 m)	échelle	réseau	211	31,000
ESO (3.6m)	HARPS	CrossDisp	visible	120,000

SOPHIE

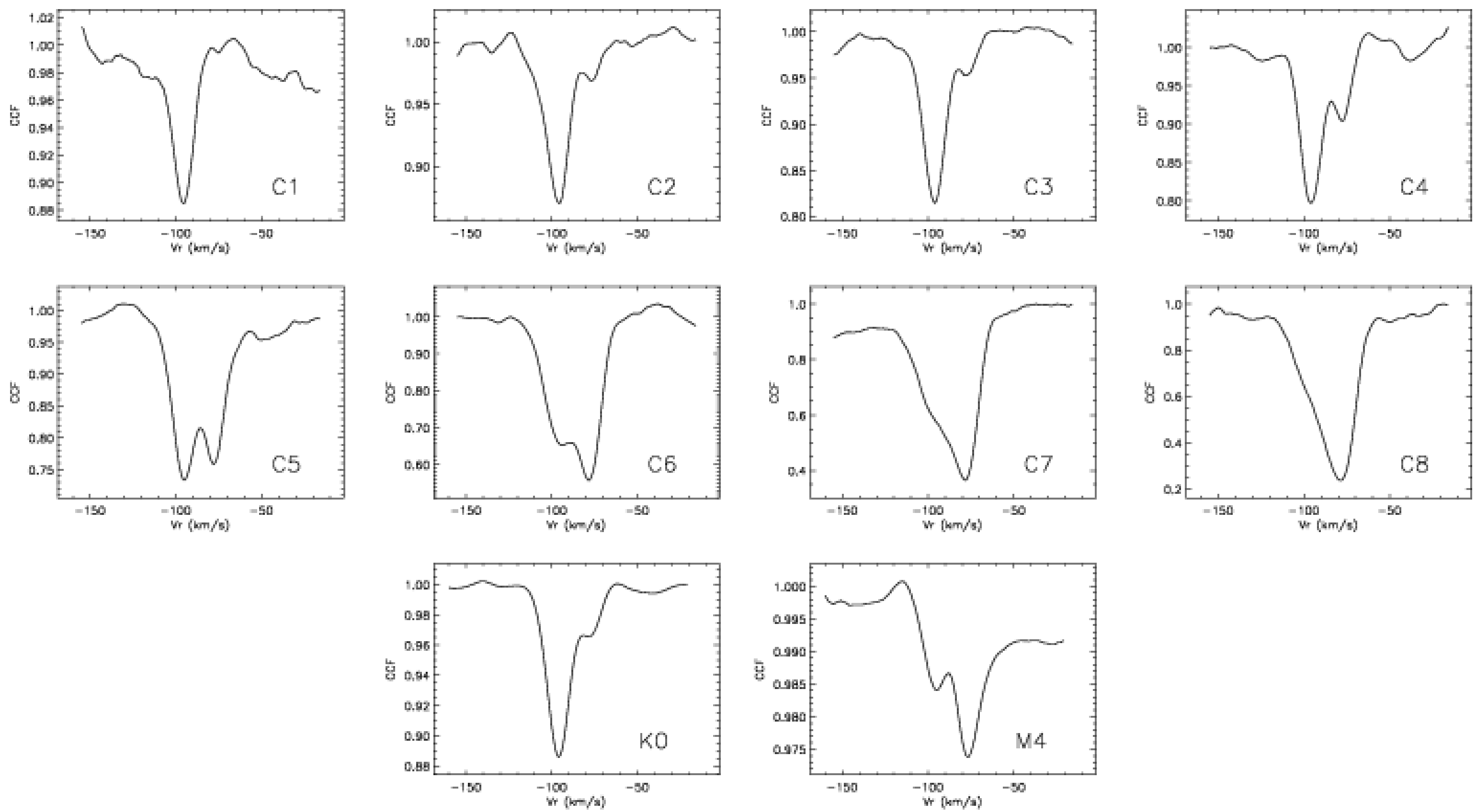

Réseau
Prisme
Lame de schmidt
Structure
Ensemble de détection
Cuve étanche
Miroir sphérique
Miroir plan percé

Correlation profile



Correlation profile

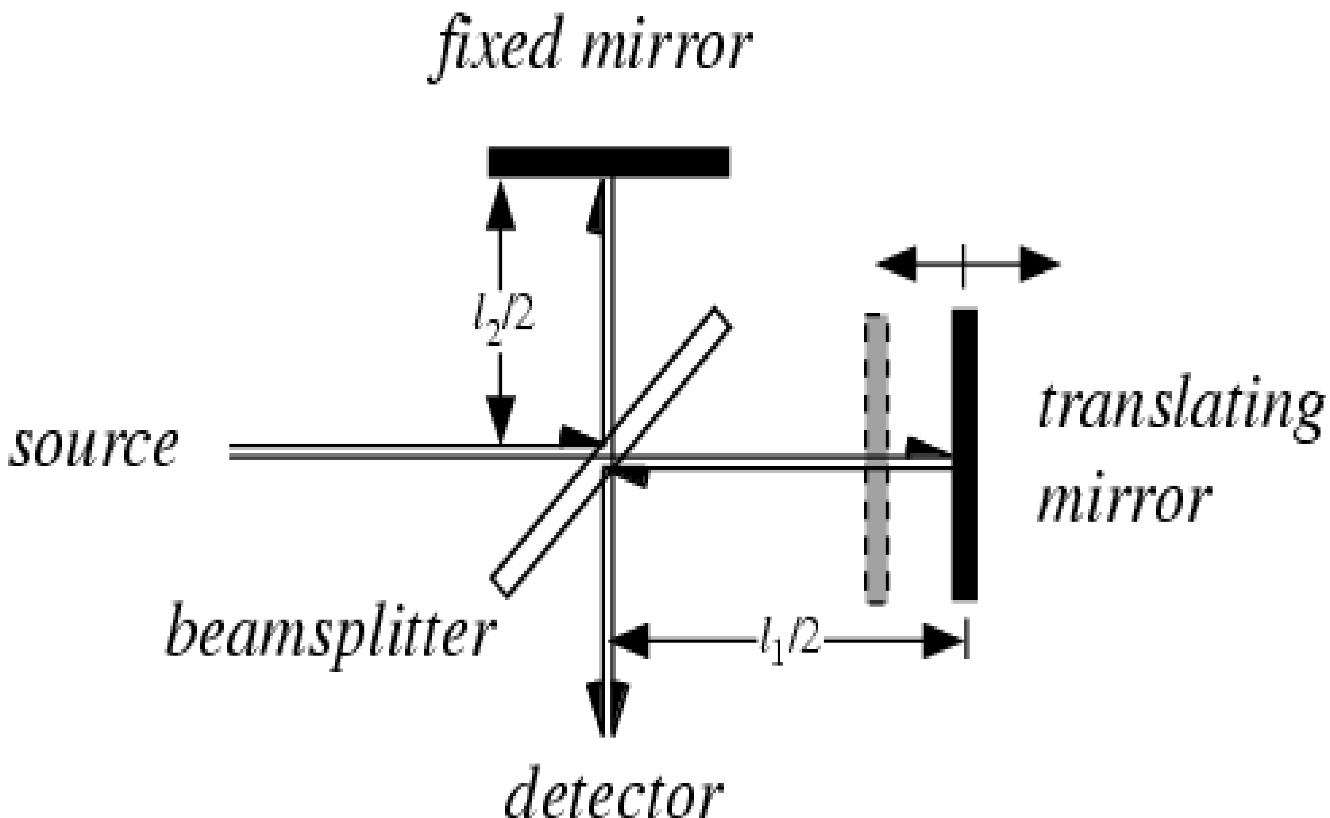
Z Oph, φ = 0.08



Fourier Transform Spectrograph

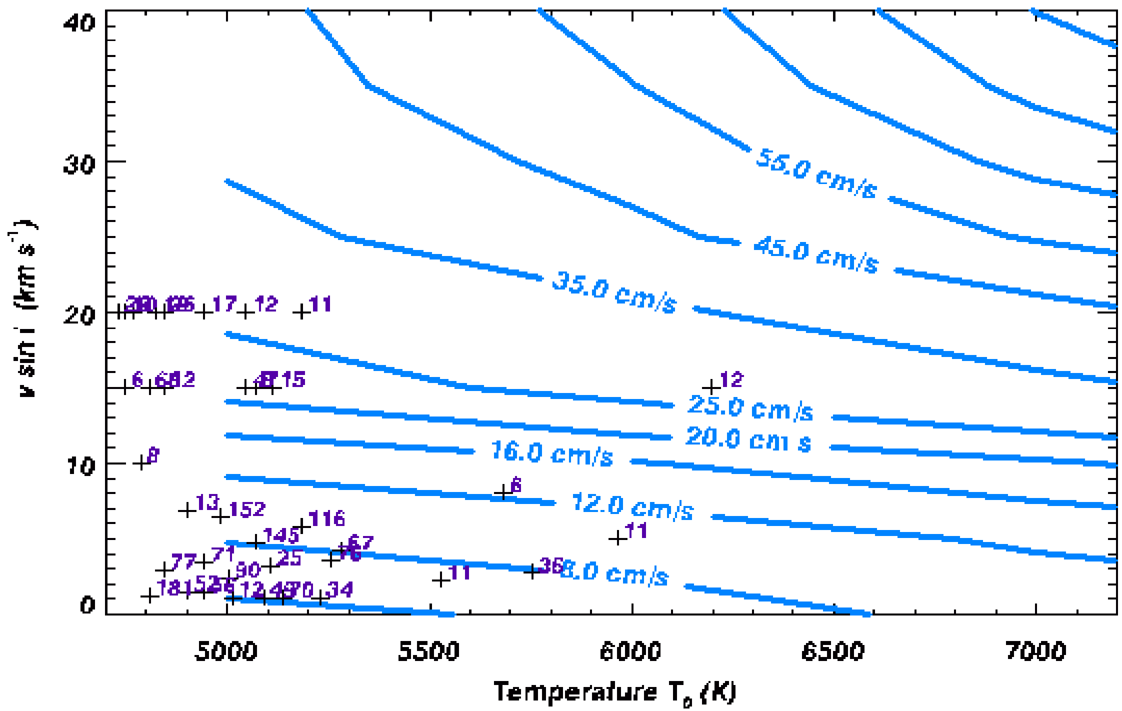
Mainly used in the IR

- → excellent instrumental profile
- → no scattered light



The SIAMOIS project

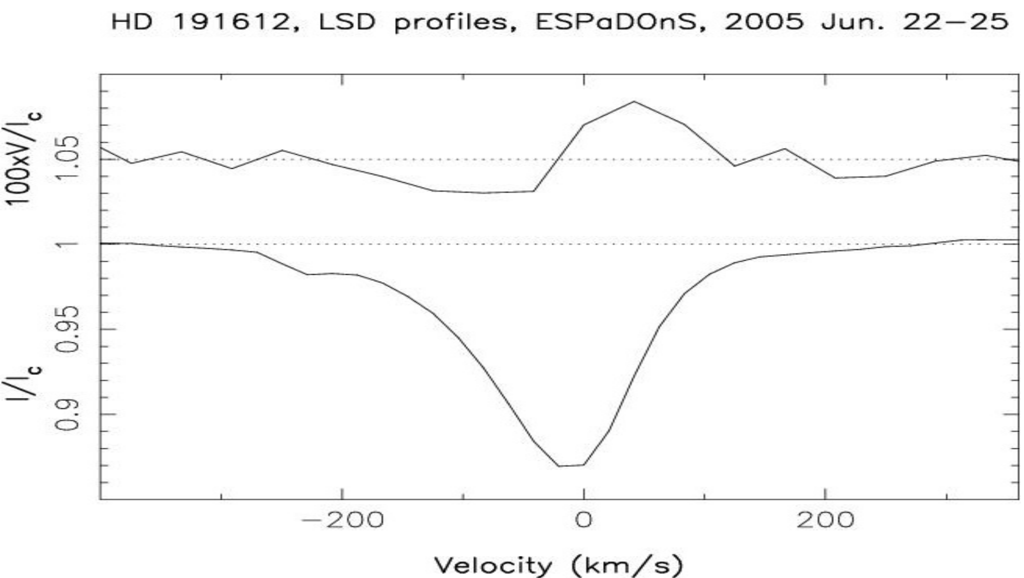
To be located at DOME C, at the focus of a 40 cm telescope
Purpose: asteroseismology of solar-like stars



Spectro-polarimetry

ESPADONS, NARVAL..

Astrophysical interests: - reflected light by solid surfaces (Moon, Mars...)
- small grain scattering (zodiacal light, reflexion nebulae...
- molecules scattering (giant planets...)
- free-free scattering (corona, hot stars envelopes...)
- Hanle effect (chromosphere, corona...)
- Zeeman effect (magnetism, spots...)



Magnetic field in a O-star

ESPADONS

Spectro-interferometry

REGAIN (GI2T), AMBER (VLTI), VEGA (CHARA)
spectral & spatial resolution