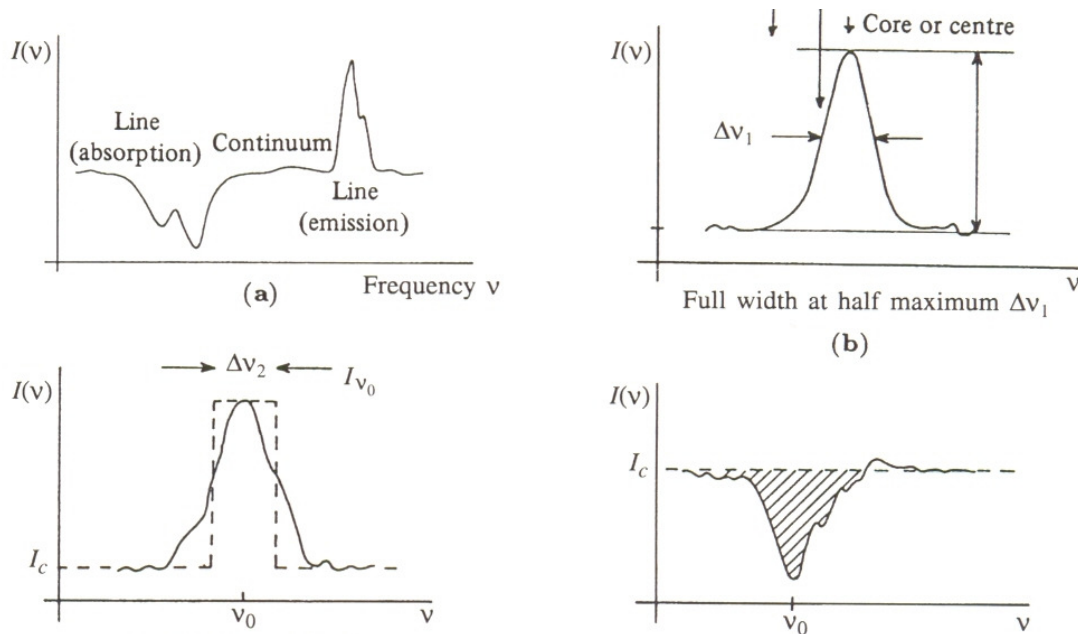


# Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

11<sup>th</sup> Lecture: 1 December 2008



Based on "Observational Astrophysics" (Springer) by P. Lena, F. Lebrun & F. Mignard, 2<sup>nd</sup> edition - Chapter 5; and other sources

## Content:

1. Spectral Line Formation
2. Information in Spectroscopy
3. General features of Spectrometers
4. Diffractive components
5. Spectrometer concepts
6. Radio spectrometers

# Spectral Line Formation

## Formation of Spectral Lines

The received radiation can be characterized by the **specific intensity**  $I(\nu, \theta)$  at **frequency**  $\nu$  and **direction**  $\theta$  and **polarization**.

At the microscopic level the transition between two energetic states  $E_1, E_2$  requires the emission or absorption of a photon of frequency  $\nu$ :

$$\nu_0 = \frac{E_2 - E_1}{h}$$

At the macroscopic level the received intensity is the sum over many such transitions, and can be described by the **transfer equation**:

$$I(\nu) = \int_0^\infty S(\nu, x) e^{-\tau(\nu, x)} dx$$

where  $S(\nu, x)$  is the source function describing the emission at point  $x$  and  $\tau$  is the optical depth between 0 and  $x$ , and  $\kappa$  the local absorption coefficient:

$$\tau(\nu, x) = \int_0^x \kappa(\nu, \xi) d\xi$$

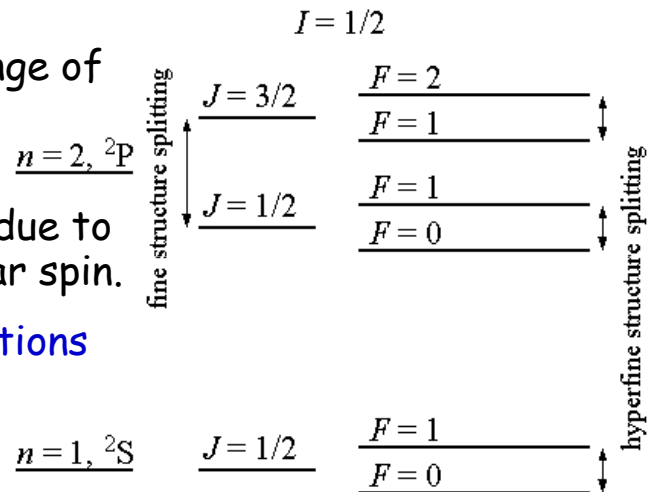
# Excitation Processes (1)

• **Electronic transitions** due to the change of the principal quantum numbers of the electronic states ( $\rightarrow$  *visible*).

• **Electronic fine structure transitions** due to the coupling of electron spin and nuclear spin.

• **Electronic hyperfine structure transitions** due to the interaction of the nuclear magnetic moment with the magnetic field of the electron.

• **Molecular transitions** such as rotational (change in angular momentum) and vibrational (change in vibrational energy) transitions\*, requiring dipole moment and moment of inertia  $I$  ( $\rightarrow$  *near-far-IR*).



$$E(J) = \hbar^2 \frac{J(J+1)}{2I}$$

\* rotational transitions are generally weaker and often coupled to vibrational transitions  $\rightarrow$  vibrational transitions split further: complex structure of **vibrational-rotational** transitions.

# Excitation Processes (2)

• **Nuclear lines** due to nuclear excitations or electron-positron annihilation ( $\rightarrow$  *MeV range*)

• **Transitions in solids** (ices) due to vibrations  $\rightarrow$  phonons ( $\rightarrow$  *near-far-IR*).

Transition	Energy [eV]	Spectral Region	Example
Hyperfine structure	$10^{-5}$	Radiofrequencies	21 cm hydrogen line
Spin-orbit coupling	$10^{-5}$	Radiofrequencies	1 667 MHz transitions of OH molecule
Molecular rotation	$10^{-2}-10^{-4}$	Millimetre and infrared	1-0 transition of CO molecule at 2.6 mm
Molecular rotation-vibration	$1-10^{-1}$	Infrared	H <sub>2</sub> lines near 2 $\mu$ m
Atomic fine structure	$1-10^{-3}$	Infrared	Ne II line at 12.8 $\mu$ m
Electronic transitions of atoms, molecules and ions	$10^{-2}-10$	Ultraviolet, visible, infrared	Lyman, Balmer series, etc. of H; resonance lines of C I, He I; K, L shell electron lines (Fe XV, O VI)
Nuclear transitions	$> 10^4$	X- and $\gamma$ -rays	<sup>12</sup> C line at 15.11 keV
Annihilations	$\gtrsim 10^4$	$\gamma$ -rays	Positronium line at 511 keV

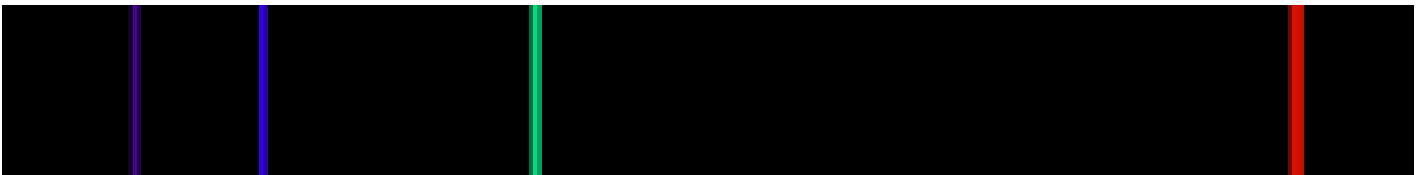
# Information in Spectroscopy

## Three General Types of Spectra

Continuous spectrum



Emission line spectrum



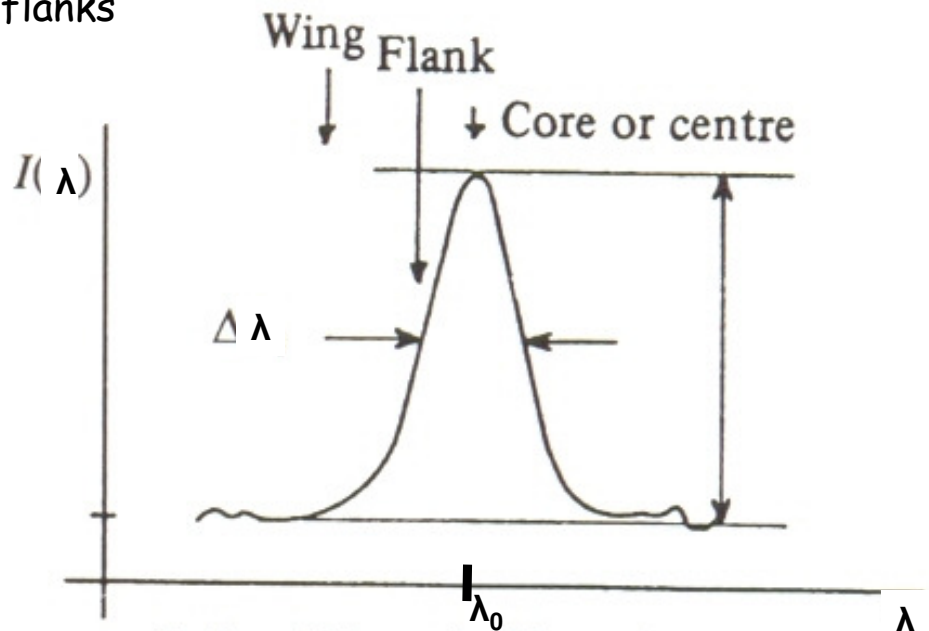
Absorption line spectrum



# Qualitative Features of a Spectrum (1)

The **line profile** is characterized by:

- the **FWHM**  $\Delta\lambda$
- the **center wavelength** or line position  $\lambda_0$
- the **flanks**
- the **symmetry** of the flanks
- the **wings**

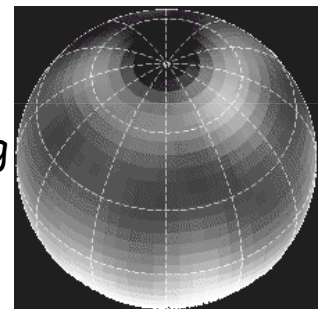


## Physical Processes causing a Line-Shift

- **Doppler effect**: the emitter is in motion relative to the observer with a relative line-of-sight velocity component  $v_{\parallel}$ . The resulting frequency shift is:

$$\Delta\nu = \nu_0 \left( 1 - \frac{\left(1 - \frac{v_{\parallel}^2}{c^2}\right)^{1/2}}{1 - \frac{v_{\parallel}}{c}} \right) \approx \nu_0 \frac{v_{\parallel}}{c}$$

→ Doppler imaging



- (normal) **Zeeman effect**: magnetic field splits line in three components (the linearly polarized  $\pi$  component at  $\nu_0$  and the two elliptically polarized  $\sigma$  components at  $\pm\Delta\nu$  with :

$$\Delta\nu = \frac{eB}{4\pi m_e} = 1.4 \cdot 10^{10} B$$

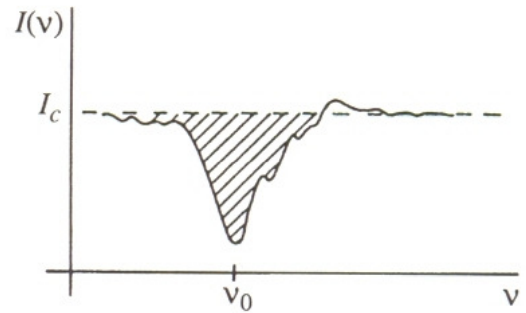
- **Einstein effect**: a strong gravitational fields causes a redshift of the light:

$$\frac{\Delta\nu}{\nu} = \left( 1 - \frac{2GM}{Rc^2} \right)^{1/2} - 1 \approx \frac{GM}{Rc^2}$$

# Qualitative Features of a Spectrum (2)

The **line intensity** describes the total power contained within the line and can be characterized by either:

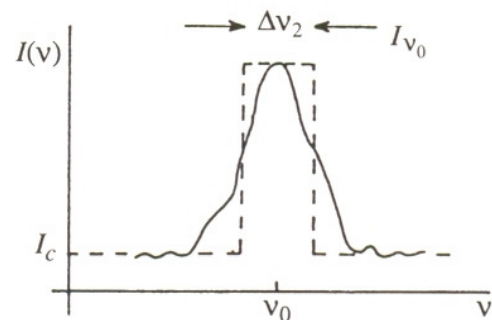
- by the **total line intensity**  $I$  (continuum subtracted)



$$\text{Intensity} \int |I(\nu) - I_c| d\nu$$

or

- by the **equivalent width**, which expresses the line flux as a rectangular window of the continuum strength at that wavelength.



$$\int (I_{\nu} - I_c) d\nu = (I_{\nu_0} - I_c) \Delta\nu_2$$

## Measuring the Spectral Line Intensity

The most common methods are:

- by **numerical integration** of the line profile:  $\int_{line} [I(\nu) - I_c] d\nu = f(N)$
- by **fitting a Gaussian**  $\phi_G(\nu) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\nu - \nu_0)^2}{2\sigma^2}\right]$  if the line profile is determined by Doppler broadening, natural broadening or the instrumental profile ("unresolved line") [see below].
- by **fitting a Lorentzian**  $\phi_L(\nu) = \frac{1}{2\pi} \frac{\Delta\nu_L}{(\nu - \nu_0)^2 + (\Delta\nu_L/2)^2}$  if the line profile is given by collisions, where  $\Delta\nu_L = 1/\pi\tau$ , with  $\tau$  the mean time between collisions. It represents homogeneous broadening in which all atoms interact in the same way within the line frequency range.
- by **fitting a Voigt profile**  $\phi_V(\nu) = \phi_G(\nu) * \phi_L(\nu)$  which is a convolution of Gaussian and Lorentzian profile (= most general case).

# General Features of Spectrometers

## Spectral Resolution (1)

The **spectral resolution** or **spectral resolving power** is defined as:

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

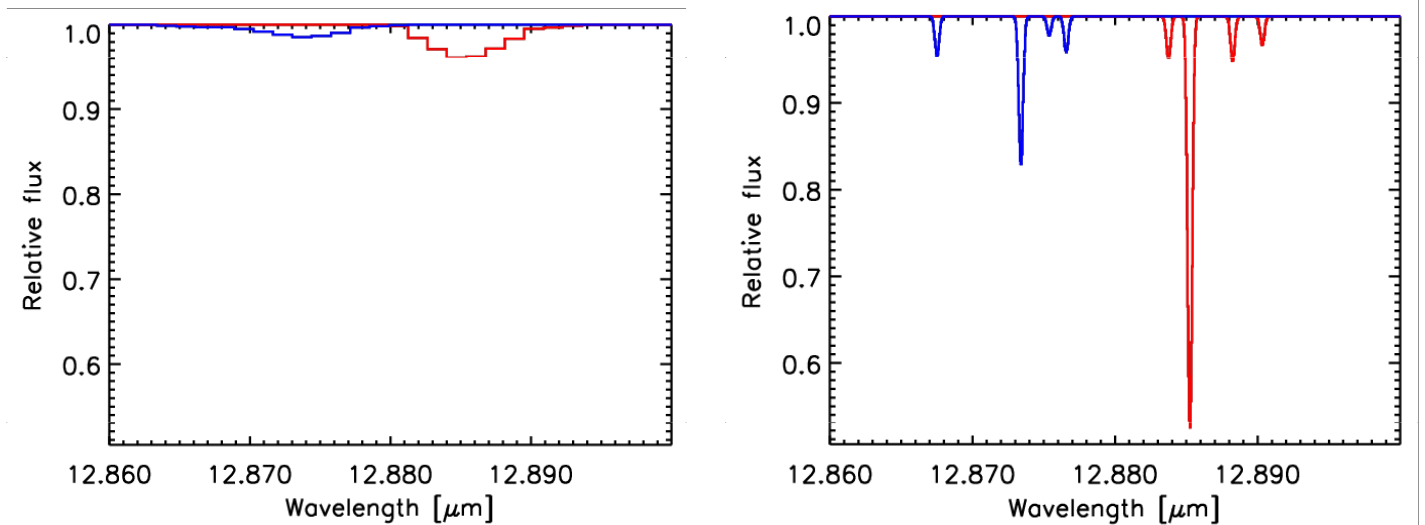
$\Delta\lambda$  is called a **spectral resolution element**.

The typical resolution that can be achieved depends on the type of spectrometer:

Spectrometer	Region	Typical resolution
Interference filter	Visible, IR	$10^2-10^3$
Grating	IR, visible, UV	$10^3-10^6$
Bragg crystal	X-ray	$10^3$
Atomic resonance	Visible, UV	$10^7$
Fabry-Perot	Visible, IR	$10^4-10^6$
Fourier transform	Visible, IR	$10^4-10^6$
Heterodyne	Radiofrequencies	$>10^6$
	IR, submillimetre	$>10^5$
Bolometer	X-ray	$10^2$
Scintillator	$\gamma$ -ray	$10^3$

# Spectral Resolution (2)

For unresolved lines, both the S/N and the line/continuum increases with increasing resolution:



Model spectra of  $C_2H_2$  at 900K and  $HCN$  at 600K (assumed Doppler broadening  $\sim 4$  km/s) at a resolutions of  $R=2000$  (left) and  $R=50000$  (right). Figure provided by F. Lahuis.

## Other Characteristics of Spectrometers

- the **instrumental profile**  $P(\nu)$  broadens a theoretically infinitely narrow line  $I_0(\nu) = \delta(\nu - \nu_0)$  to the observed line width:

$$I(\nu) = P(\nu) * I_0(\nu)$$

Usually the instrumental profile determines the spectral resolution element, which is typically Nyquist-sampled.

- the **beam étendue** determines the light gathering power of the instrument. Larger étendues require larger dispersive elements ( $A$ ) or highly inclined beams ( $\Omega$ ).

- the **transmission** determines the throughput  $t(\nu) = \frac{I_{exit}(\nu)}{I_{entry}(\nu)}$



# Diffractive Components

## Interference Filters

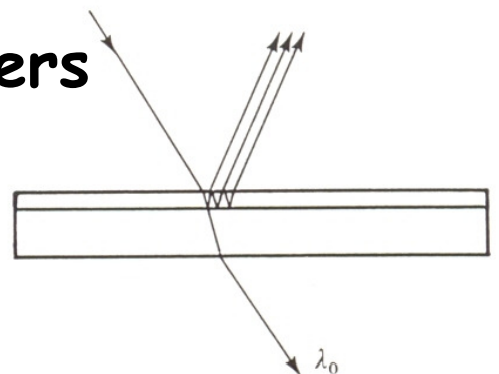
Principle: maximum transmission

at  $\lambda_0$  where  $\frac{2n_1d}{\lambda_0} + \frac{\pi}{2} = 2k\pi$

Destructive interference at  $\lambda_0 \pm \Delta\lambda$ .

Refractive indices

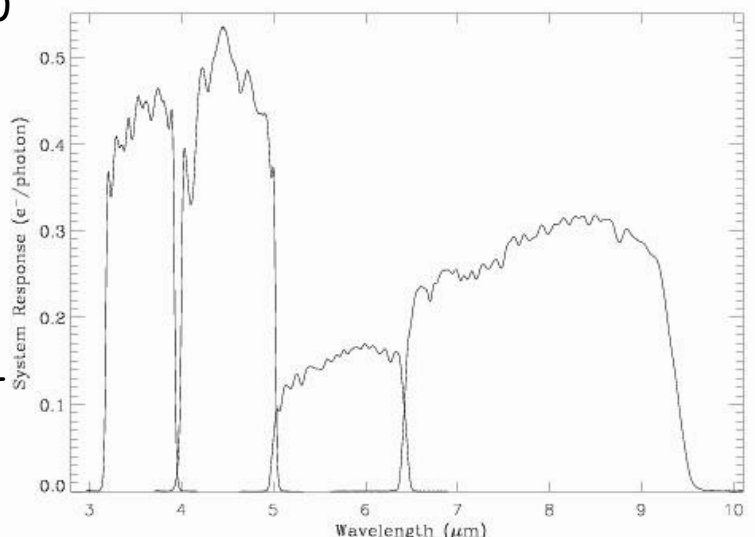
$n_1(\lambda)$   
 $n_2(\lambda)$



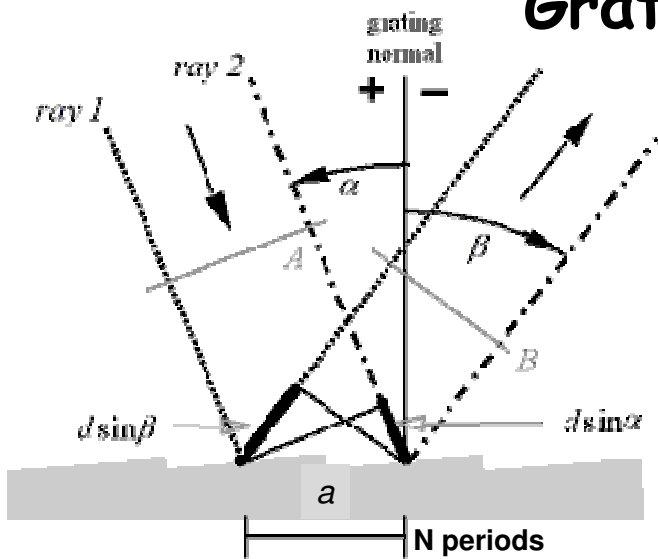
Other wavelengths (for which the above equation is also satisfied) are absorbed by a blocking or **absorbing filter**. Note:

- spectral resolution  $R \sim \text{few} - 1000$
- often  $>10$  **interference layers**
- filters are often tilted to avoid reflections  $\rightarrow$  shift of  $\lambda_0$ .

The opposite are **neutral density filters**, which provide wavelength-independent attenuation.



# Gratings



Constructive **interference** occurs at:

$$a \cdot (\sin \alpha \pm \sin \beta) = m \lambda$$

The **maximum resolution** is then given by:

$$R = mN$$

(often limited by the pupil diameter)

A light bulb of a flashlight seen through a transmissive grating, showing three diffracted orders. The order  $m = 0$  corresponds to a direct transmission of light through the grating. In the first positive order ( $m = +1$ ), colors with increasing wavelengths (from blue to red) are diffracted at increasing angles.  
Source: Wikipedia

## Blazed Gratings

Generally, the energy of the beam diffracted by a periodic structure is uniformly distributed over the different orders  $m$ . If we observe only one order this is very inefficient.

For **blazed gratings** the *directions of constructive interference and specular reflection coincide*:

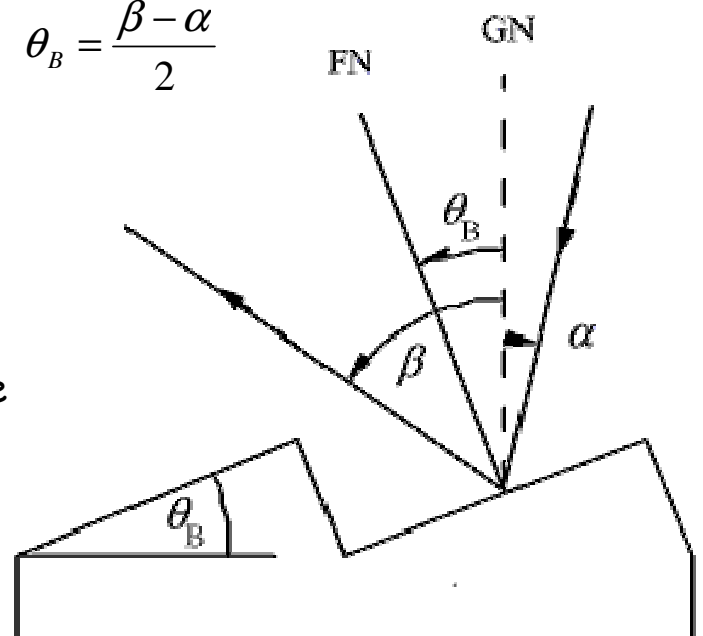
$$\alpha + \beta = 2(\alpha + \theta_B) \Rightarrow \theta_B = \frac{\beta - \alpha}{2}$$

**Advantage:**

- High efficiency

**Disadvantage:**

- Blaze angle  $\theta_B$  (and hence blaze wavelength  $\lambda_B$ ) are fixed by construction.



# Echelle Gratings

Echelle gratings use:

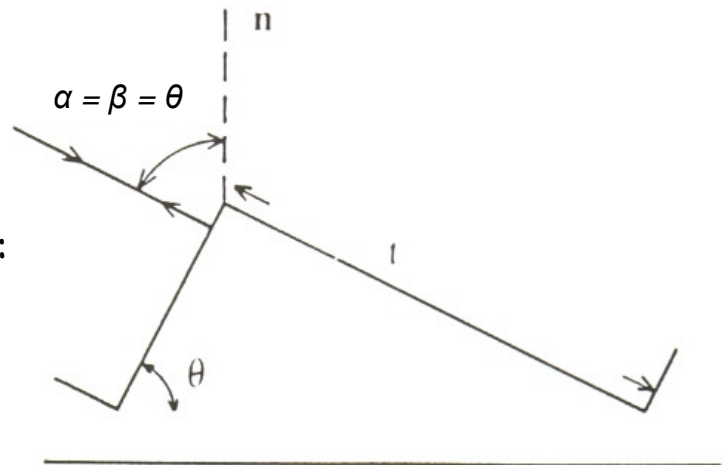
1. a very high order of diffraction  $m$
2. a large groove period  $a \gg \lambda$
3. a high angle of incidence ( $\alpha = \beta = \theta$ )  $\rightarrow$  Littrow condition

In Littrow configuration:

$$m\lambda_B = 2a \sin \Theta$$

The resolution for a slit width  $L$  and a collimator focal length  $f_{coll}$  is:

$$R = 2 \tan \theta \frac{f_{coll}}{L}$$



$\rightarrow$  Echelle gratings achieve high resolution ( $R = mN$ ) and high dispersion ( $\sim m/a$ ).

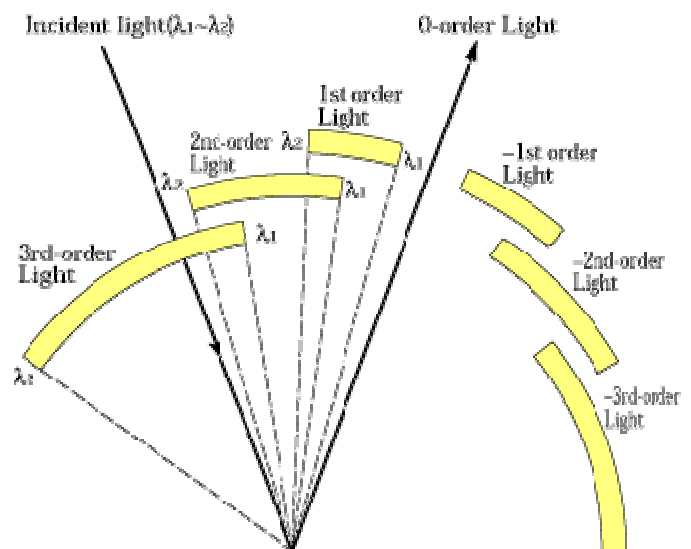
## Free Spectral Range and Cross Dispersion

The different diffraction orders overlap with each other:

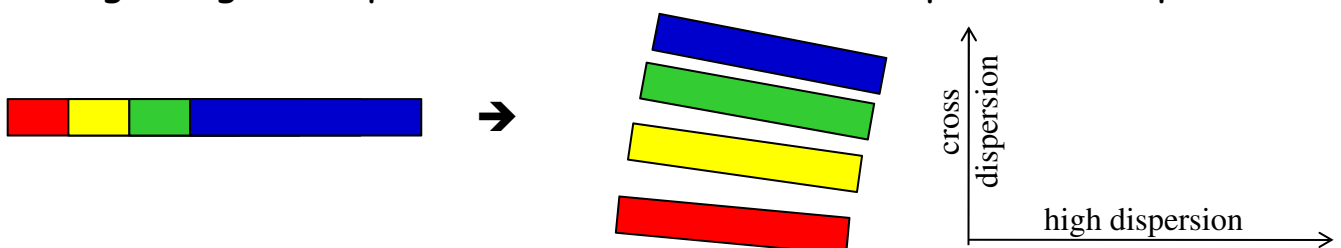
$$m\lambda = a(\sin \alpha + \sin \beta) = (m+1)\lambda'$$

The free spectral range is the largest wavelength range for a given order that does not overlap the same range in an adjacent order.

$$\Delta\lambda_{free} = \lambda - \lambda' = \frac{\lambda'}{m}$$



An additional element with a dispersion direction perpendicular to that of the grating will separate the orders and avoid spatial overlap.

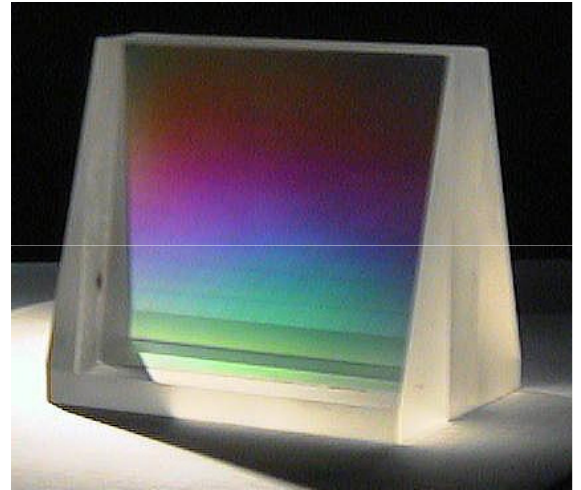


# Holographic and Immersion Gratings

Interference pattern of two laser beams  
→ expose on photoresist coating →  
chemical etching → **holographic grating**.

*Advantage:* little scattered light

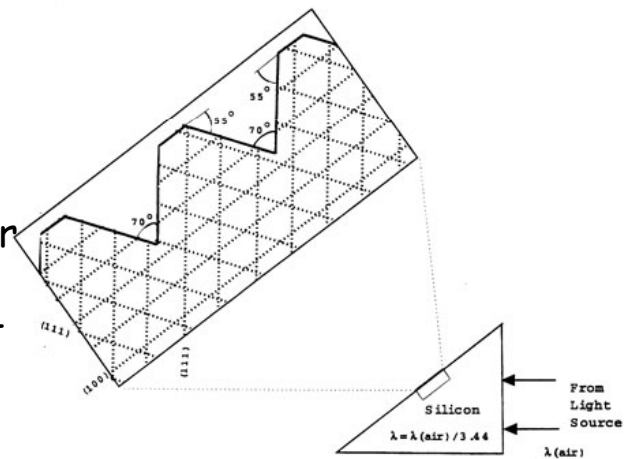
*Disadvantage:* cannot be blazed due to sinusoidal groove profile → low efficiency



**Immersion gratings** are reflection gratings in which light passes through a medium with high refractive index  $n$  before hitting the diffraction grating.

*Advantages:*  $n$  times higher resolution for same size, and: coarse grooves enable continuous wavelength coverage in cross-dispersed mode.

*Disadvantage:* limited wavelength ranges



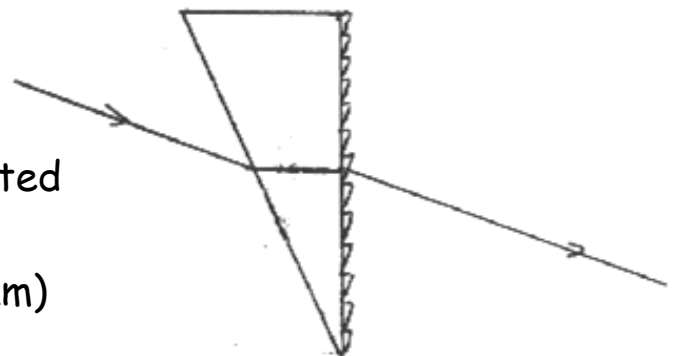
## Grisms

Grism = transmission **GR**ating + **prISM**

For a given wavelength and diffraction order the refraction of grating and prism may compensate each other and the optical axis remains (almost) unchanged

*Advantages:*

- ideal to bring in and out of a collimated beam ("filter wheel")
- reduces coma (if non-collimated beam)



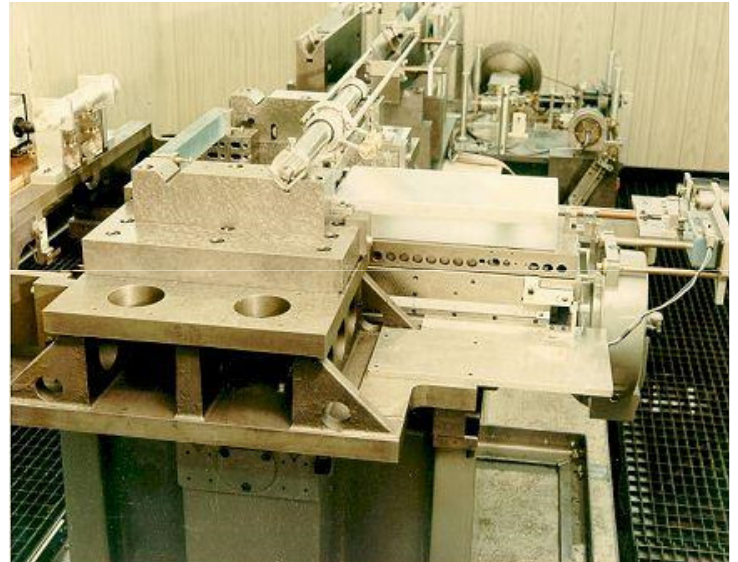
*Disadvantage:*

- difficult to manufacture (either by replication and gluing or by direct ruling).

# Grating Production

Common techniques:

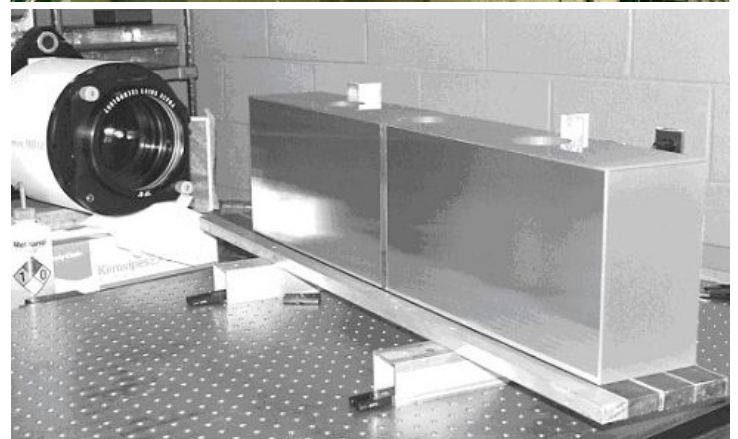
- Direct ruling
- Replication
- Etching



*Above: MIT 'B' Engine. This ruling engine, now in operation at Newport, is shown with its cover removed.*

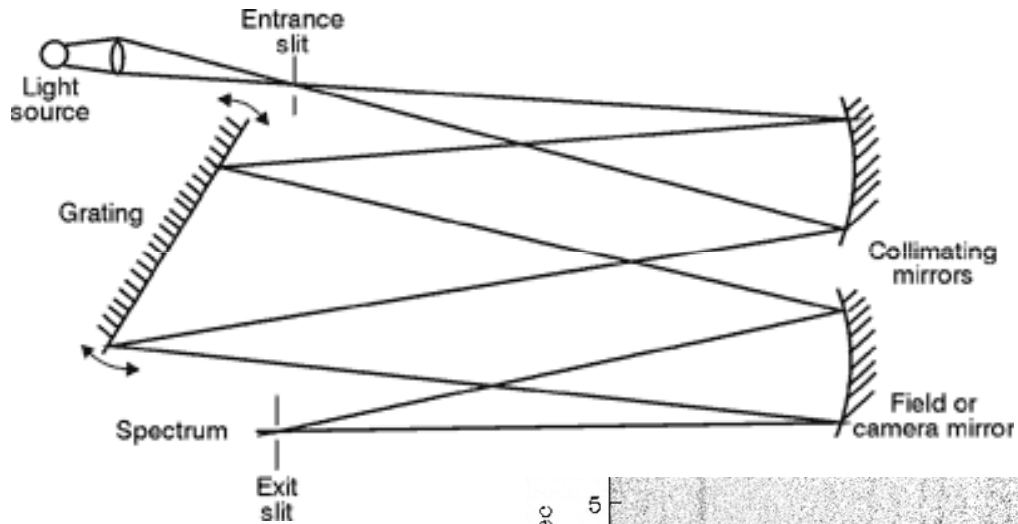
*Below: A large mosaic grating. A monolithic 214 x 840 mm replica mosaic grating was produced from two 214 x 415 mm submasters.*

*Source: NEWPORT Grating Handbook*



# Some Spectrometer Concepts

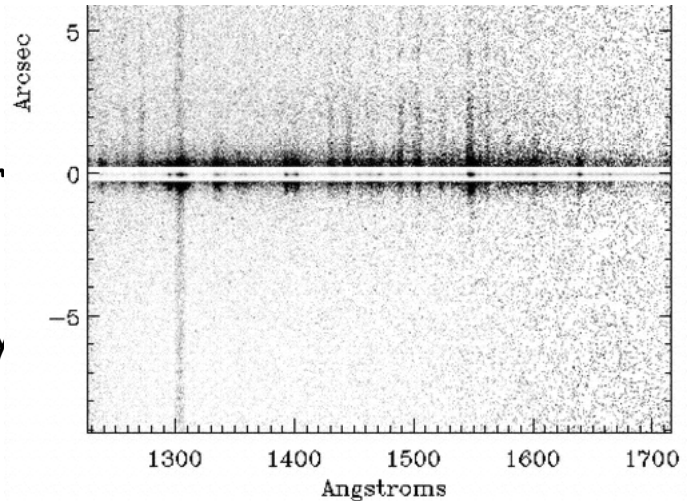
# Single Slit Spectrometers



Still the most common spectrometer.

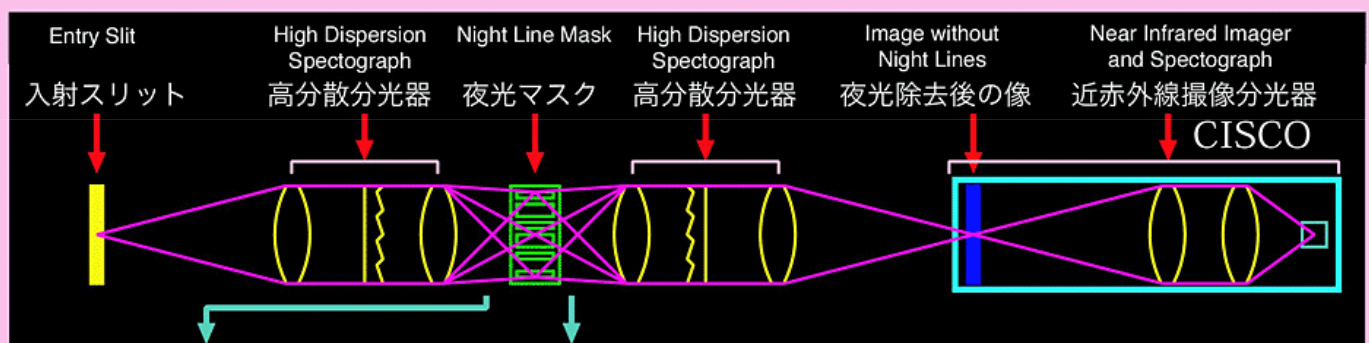
*Advantage:* simple and efficient; easier to calibrate and build

*Disadvantage:* only one spectrum at a time → not suitable for spectral survey or spectral maps of larger regions

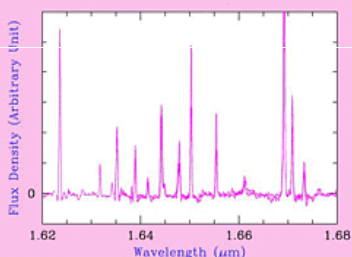


# OH Suppression Spectrographs

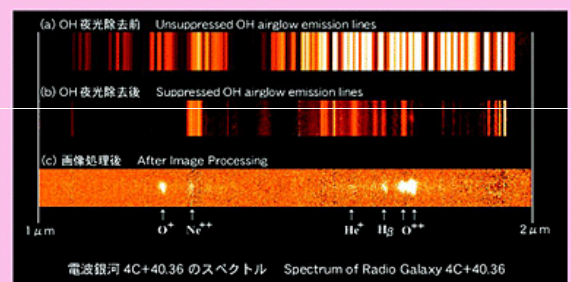
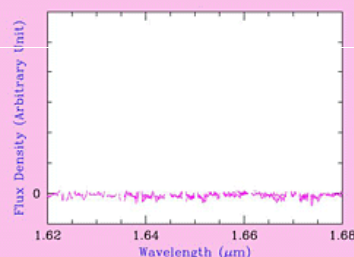
OHS filter out the wavelengths of atmospheric OH lines, which contribute the major part of the near-IR background.



夜光輝線除去前  
Before Removing Night Lines



夜光輝線除去後  
After Removing Night Lines



# Multi-object Spectrographs (1)

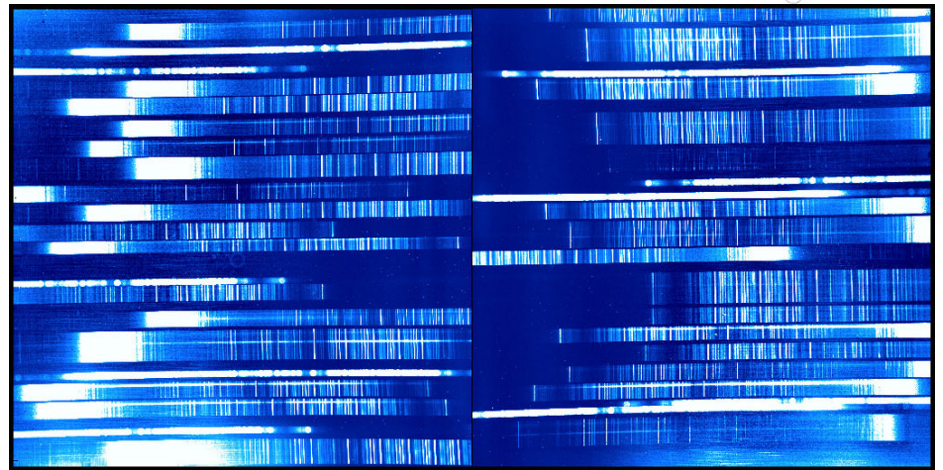
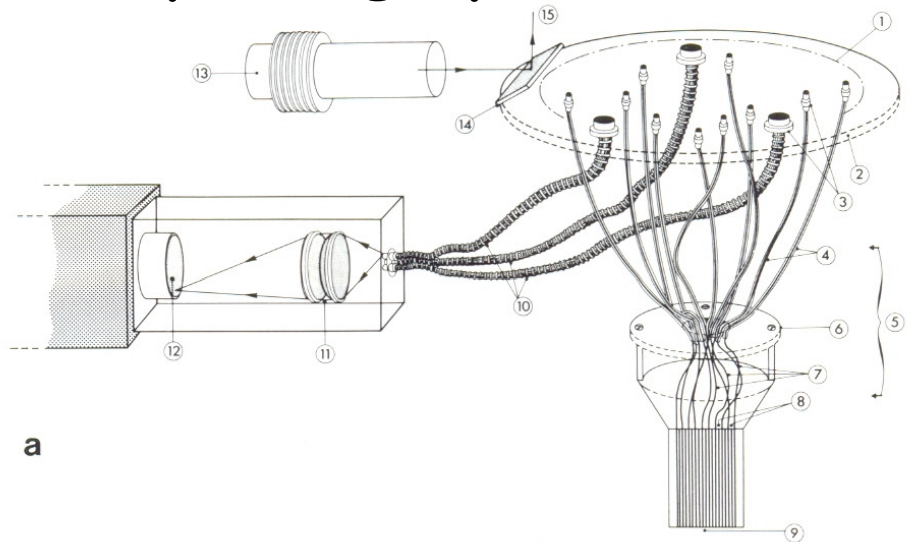
Multiple source pick-ups in the focal plane; light transport e.g. by fibers.

*Advantage:*

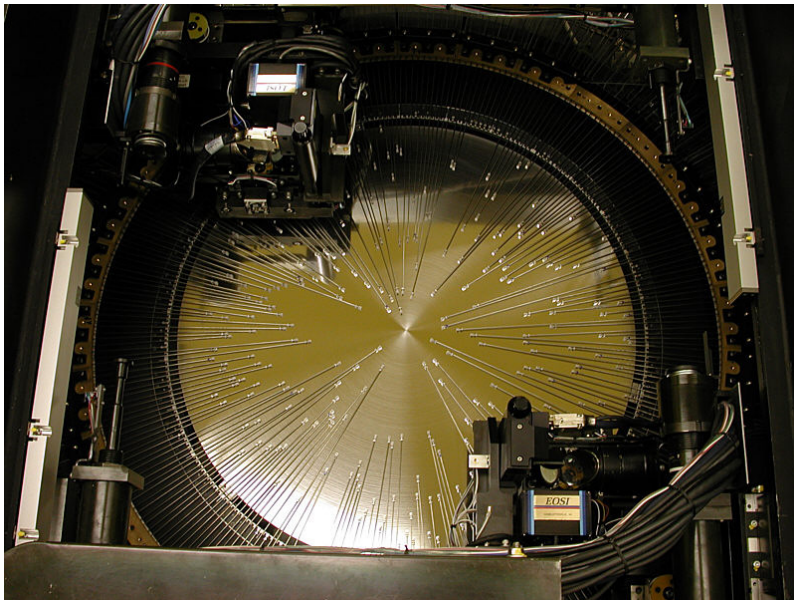
up to thousands of spectra simultaneously.

*Disadvantages:*

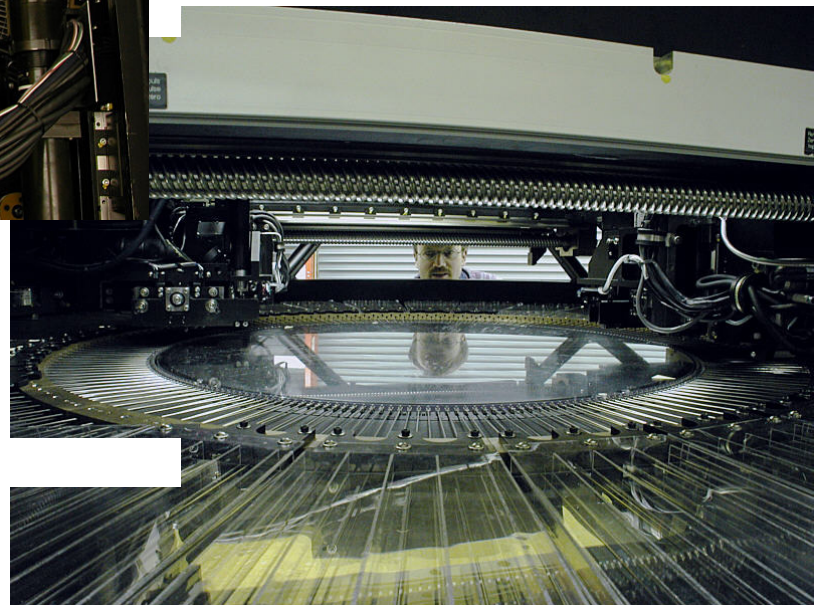
complex mechanism to position the fibers,  
fiber transmission limits wavelength range,  
compact objects



# Multi-object Spectrographs (2)

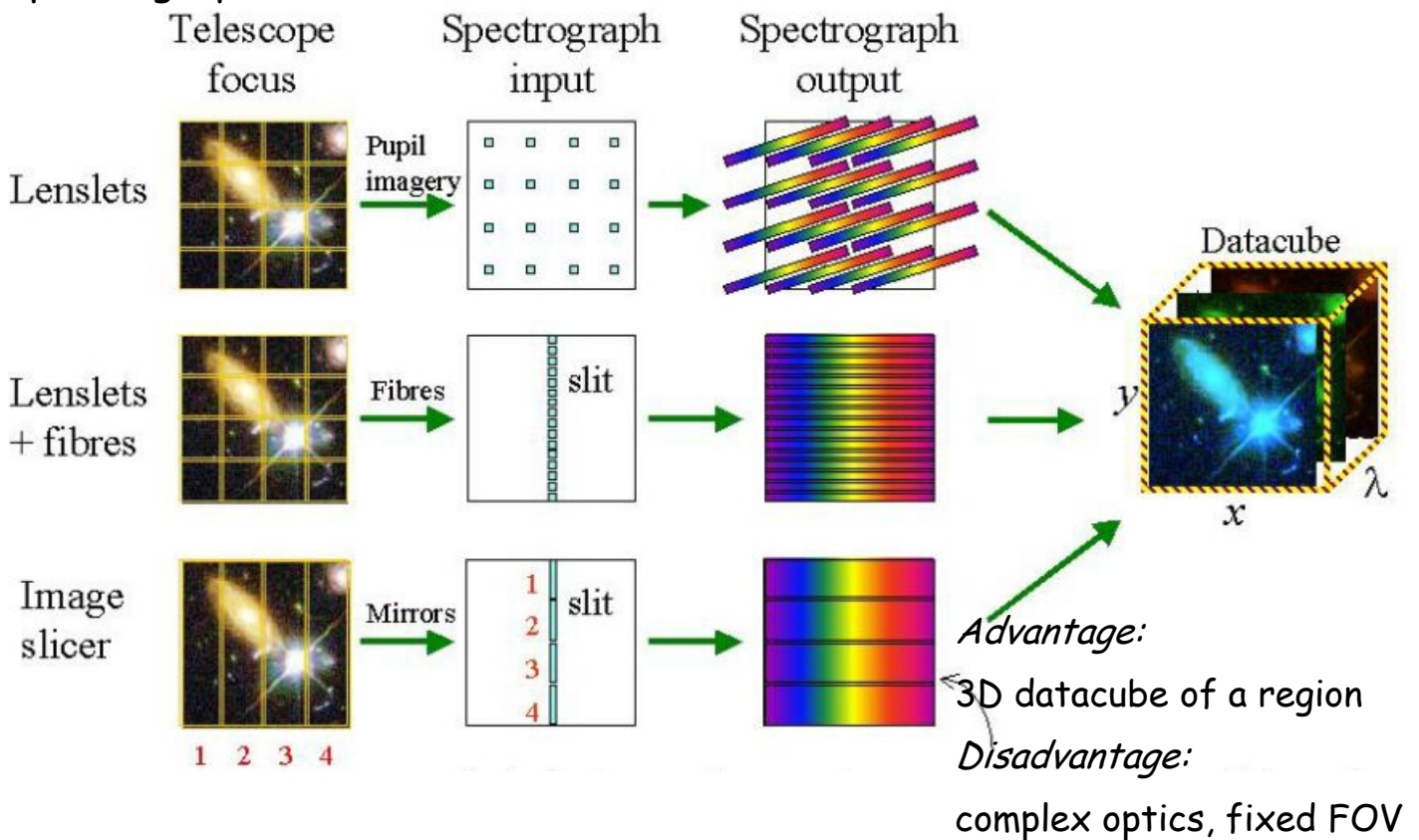


Example: Hectospec (SAO)  
with robotic positioning of the fibers

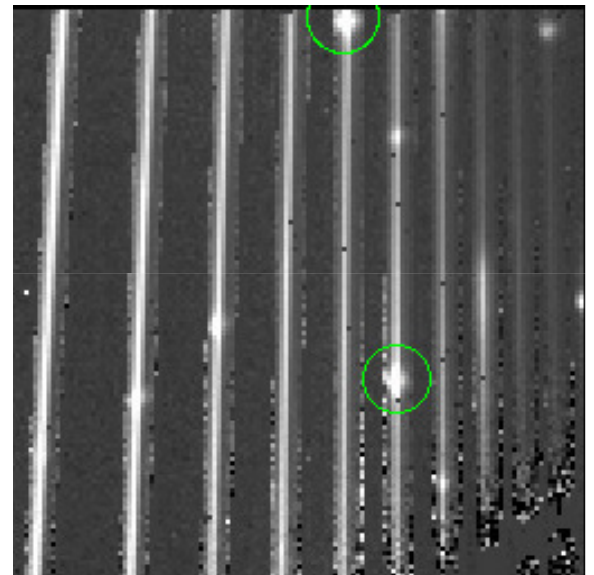
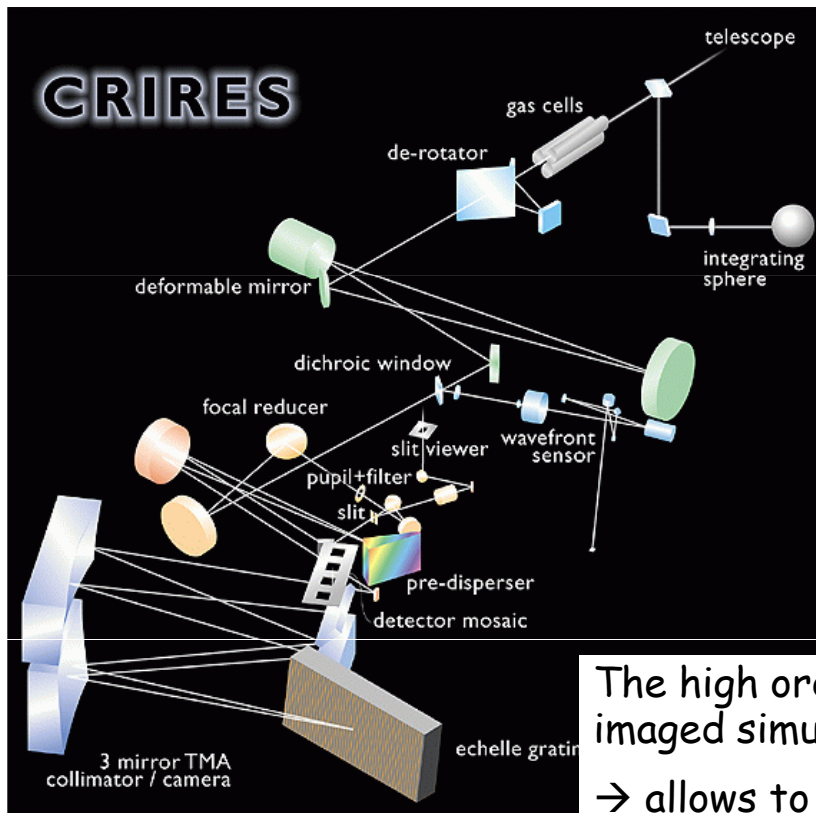


# Integral Field Spectrographs

*Concept:* cut an area on the sky in several adjacent slices or sub-portions, realign them optically into one long slice and treat it as a long slit spectrograph.



## Echelle Spectrographs (2)



The high orders are close together and imaged simultaneously on the same array.

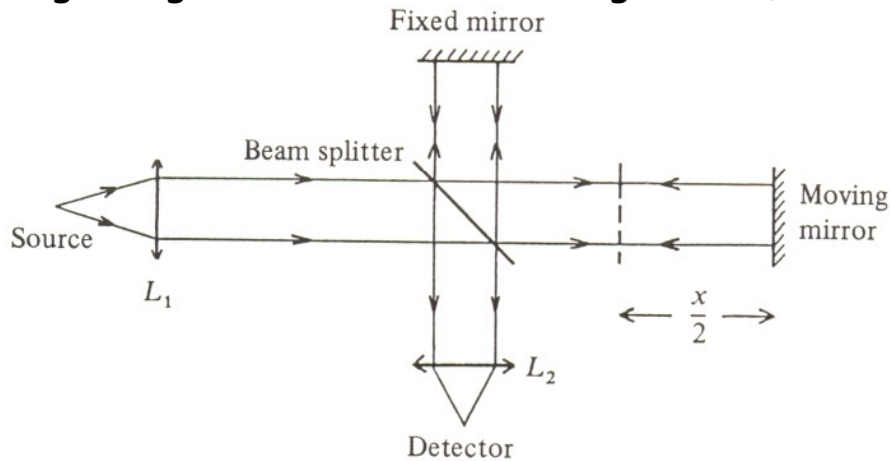
→ allows to "expand" a single-slit spectrum to a length many times the size of the detector.

→ high resolution.



# Fourier Transform Spectrometer (1)

The FTS or Michelson interferometer is a two-wave interferometer (as opposed to a grating with N waves from N grooves ).



If  $x$  is the difference in path length the intensity of a monochromatic wave of intensity  $I_0$  and wave number  $\sigma$  is:

$$I(x) = \frac{I_0}{2} (1 + \cos 2\pi\sigma x)$$

A source with a spectral distribution  $I_0(\sigma)$  in the range  $[\sigma_1, \sigma_2]$  has:

$$I(x) = \frac{I_0}{2} \int_{\sigma_1}^{\sigma_2} I_0(\sigma) (1 + \cos 2\pi\sigma x) d\sigma$$

# Fourier Transform Spectrometer (2)

The signal is an interferogram. It is the Fourier transform of the spectrum of the object.

→ For each setting of the spectrometer arm length (value of  $x$ ) all spectral elements contribute to the signal ("spectral multiplexing").

A FTS measures the temporal coherence of the signal.

The source spectrum  $I_0(\sigma)$  (frequency domain) can be recovered via inverse Fourier transform  $I'_0(\sigma) = FT[I(x) - \langle I(x) \rangle]$

with the mean value:  $\langle I(x) \rangle = \frac{1}{2} \int_{\sigma_1}^{\sigma_2} I_0(\sigma) d\sigma$

For a finite interval in  $x$   $[-x_m/2, +x_m/2]$  one gets  $I'_0(\sigma) = I_0(\sigma) * \text{sinc}(x_m \sigma)$   
i.e. the recovered spectrum is degraded in resolution. The resolution is:

$$R = \frac{\sigma_0}{\Delta\sigma} = x_m \sigma_0$$

# Fourier Transform Spectrometer (3)

Now: considering the maximum beam étendue beyond which the resolution would be degraded:

At the same resolution the throughput of an FTS can be ~100-1000 higher than that of a grating spectrometer ("throughput advantage").

Notes: FTS (like FPS) are axisymmetric and particularly suited to observe extended sources.

Since the *whole* integration time is used for *each* spectral element - as compared to a scanning monochromator - an FTS will produce a

gain of  $G = \frac{\sqrt{M}}{2}$  in the S/N of the resulting spectrum

(where  $M$  is the number of spectral elements and the dominating noise is detector noise).

This is called the Fellgett advantage (or multiplex advantage).

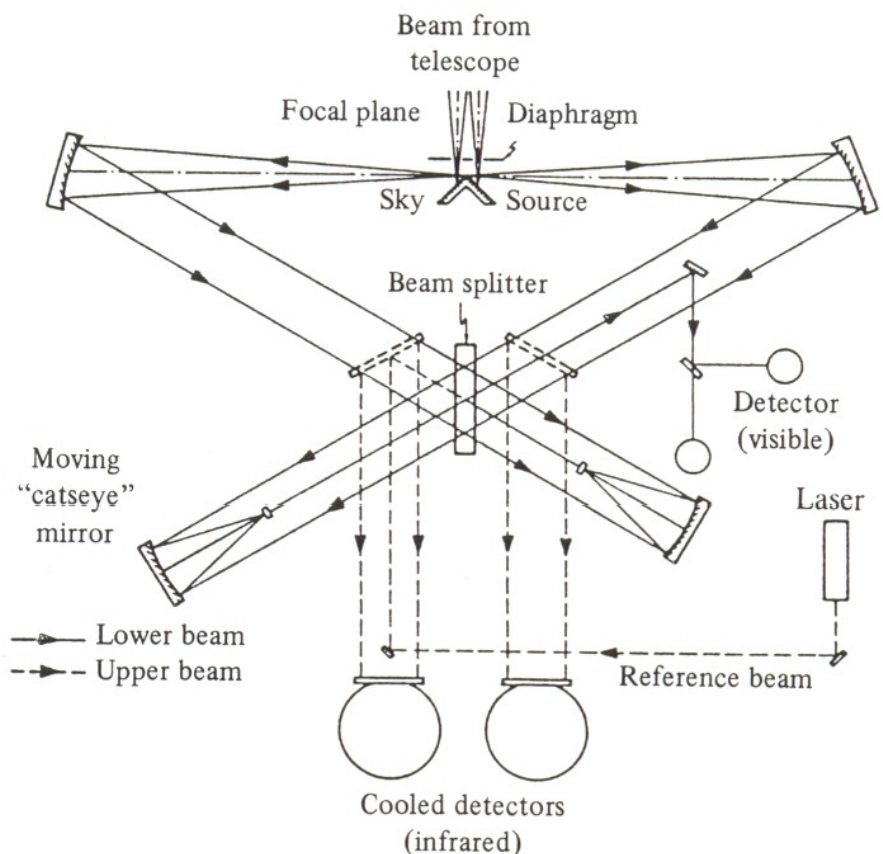
# Fourier Transform Spectrometer (4)

Example: the FTS of the CFHT mounted at the Cassegrain focus (Maillard & Michel 1982)

Symmetrical setup.

A HeNe laser provides reference fringes to control the sampling.

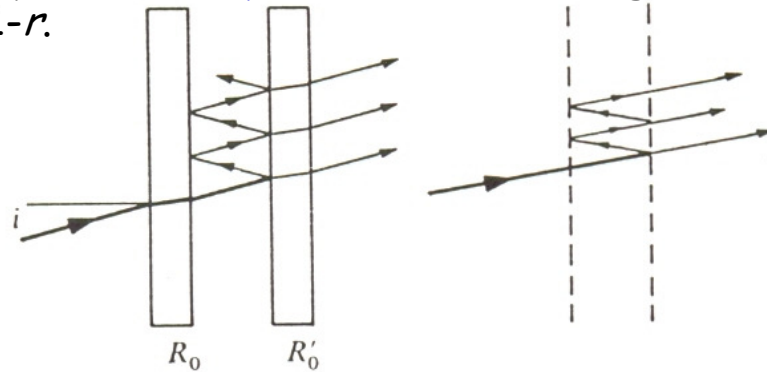
The quantity  $\frac{I_1 - I_2}{I_1 + I_2}$  is independent of atmospheric fluctuations



# Fabry-Perot Spectrometer (1)

Combines the throughput advantage of the FTS ( $Q=2\pi$ ) with very high spectral resolution while being more compact.

Principle: two parallel plates (Fabry-Perot etalon) of high reflectivity  $r$  and transmission  $t = 1-r$ .



The transmission is 
$$I = I_0 \left( \frac{r}{1-r} \right)^2 \left[ 1 + \frac{4r}{(1-r)^2} \sin^2(2\pi d \sigma \cos i) \right]^{-1}$$

and has transmission peaks when  $\sigma = \frac{m}{2d}$

$m$  is the order of the interferometer and  $\Delta\sigma = 1/2d$  the free spectral interval.

# Fabry-Perot Spectrometer (2)

An important quantity characterizing a FPS is the finesse  $F = \frac{\pi\sqrt{r}}{1-r}$

since it determines the resolution  $R = \frac{\sigma}{\Delta\sigma} = mF$

The maximum throughput of a FPS is given by  $U = 2\pi \frac{S}{R}$   
where  $S$  is the area of the etalon.

*Advantages:*

- simultaneous spectroscopic information over a large field

*Disadvantages:*

- needs a pre-disperser to isolate a free spectral interval
- good for line spectroscopy, not practical for extended spectral range

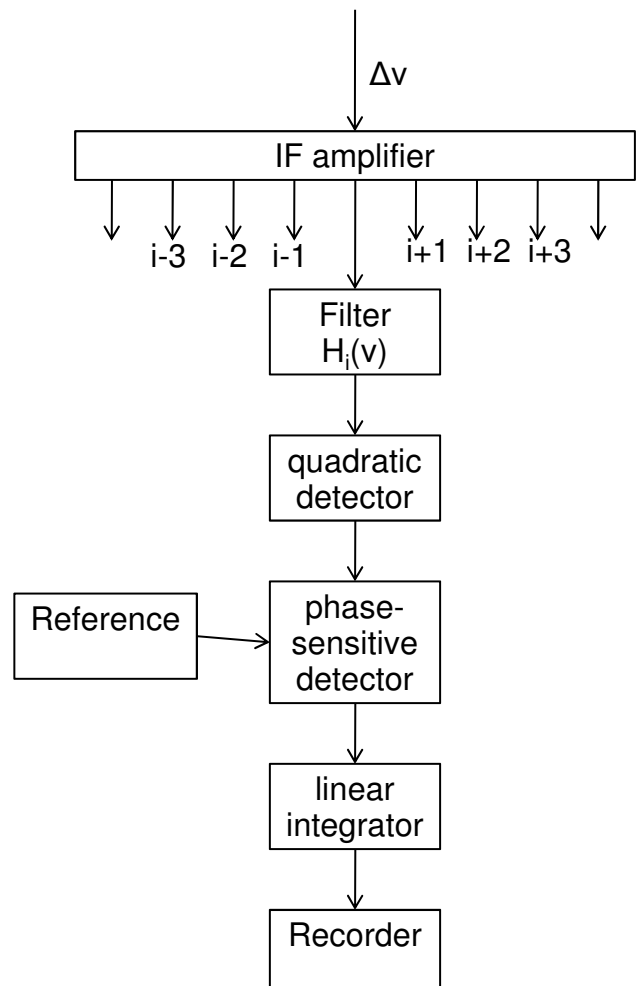
# Radio Spectrometers

## Multichannel Spectrometers

1. IF signal leaving the mixer
2. set of filters with bandpass  $B$  split the frequency band  $\Delta\nu$  in  $N=\Delta\nu/B$  channels.
3. Each filter is followed by a quadratic detector and a commutator comparing the signal with a calibration reference.

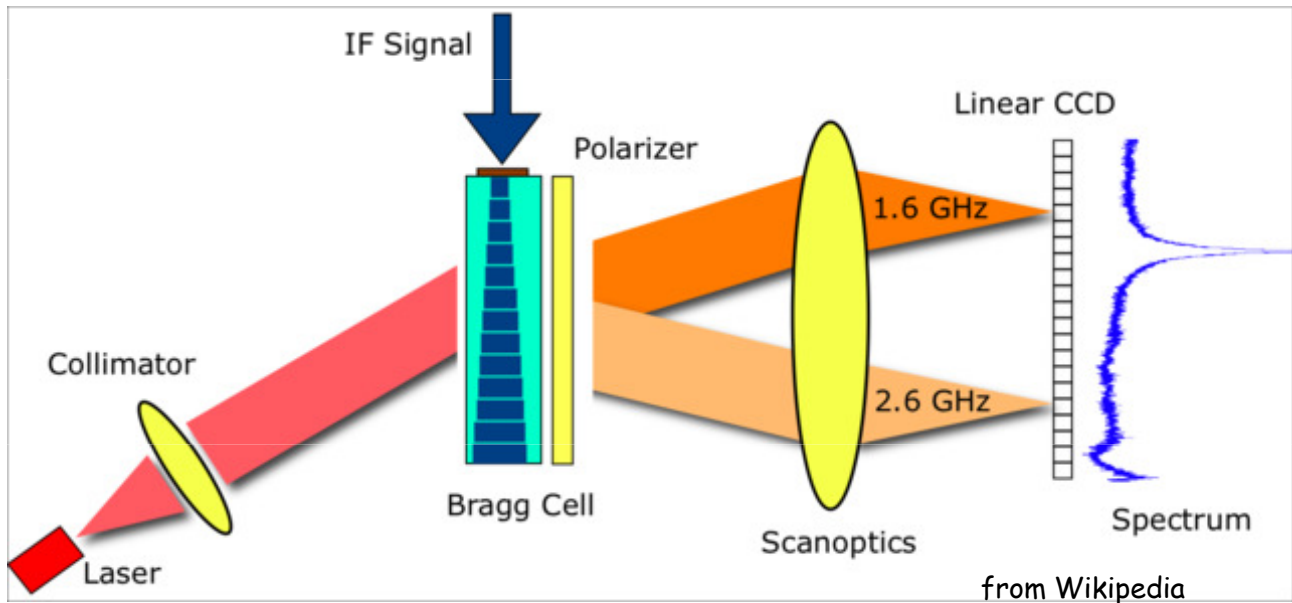
The resolution is given by:  $R = \frac{V_0}{B}$   
where  $B$  can be very narrow.

Multi-channel spectrometers can have up to 512 parallel channels.



# Acousto-Optical Spectrometer

An AOS converts the frequencies to ultrasonic waves that disperse a monochromatic light beam onto an array of visible light detectors.



The acoustic wave can be created in a crystal ("Bragg-cell") and modulates the refractive index  $\rightarrow$  induces a phase grating. The angular dispersion is a measure of the IF-spectrum.

## Autocorrelation Spectrometers

**Reminder** of lecture on Fourier transforms:

$f(x)$	Function
$\tilde{f}(s) = FT\{f(x)\}$	Fourier transform of $f(x)$
$ \tilde{f}(s) ^2$	Spectral density or power spectrum of $f(x)$
$ \tilde{f}(s) ^2 = f(x) \otimes f(x)$	Wiener - Khinchine (autocorrelation) theorem
$k(x) = \int_{-\infty}^{+\infty} f(u)f(u+x)du$	Autocorrelation

**Principle of the autocorrelator:**

Spectrum  $I(\nu)$  is the Fourier transform of the autocorrelation of  $x(t)$ , a time-dependent IF signal  $\rightarrow$  digitize  $x(t)$  and compute the autocorrelation function  $R(\tau) =$  spectrum of  $x(t)$