Introduction to Astronomical Spectroscopy

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Outline

- **Introduction**
- **Telescope & Spectrometer**
- **Spectral Line Characteristics**
- **Spectrometers**
- **Spectral Data Reduction**
- **References**

Astronomical Spectroscopy

The use of spectroscopy (the analysis of light as a function of wavelength) as a tool for obtaining observational data on the chemical compositions, physical conditions, and radial velocities of astronomical objects. Astronomical applications of optical spectroscopy from ground-based observatories cover the electromagnetic spectrum from the near-ultraviolet (wavelengths around 0.3 micrometer) through the visible (0.4-0.7μm) and into the near-infrared (2μm). Space-based observatories extend spectroscopic observations from the far-ultraviolet (0.1μm) to the far-infrared (100μm).

Astronomical Spectroscopy ...contd.

Usually a spectrograph is fitted to a reflecting telescope, which serves as a light collector. The image of the celestial body being studied is focused on the spectrograph slit, which limits the region under study (thus improving the spectral resolution) and reducing the contribution by the night sky. The diverging light beam then passes from the slit to a collimator (either a lens or mirror).

Astronomical Spectroscopy ...contd.

This produces parallel light, which is then dispersed by a diffraction grating or prism. The dispersed light enters a camera, which focuses the spectrum onto a detector, either a charge-coupled device (CCD) in the case of an optical spectrograph, or an electronic array sensitive to infrared light.

It is often desirable to obtain spectroscopy of many of the objects within a telescope's field of view in a single exposure. A variety of methods are available to accomplish such surveys, including slitless spectroscopy, slitlet masks, and fiber-fed spectroscopy.

Astronomical Spectroscopy ...contd.

It is possible to take spectra of all of the brighter objects within the field of view by not using a spectrograph at all, but by combining a low-dispersing element directly with the telescope. For instance, an objective prism may be placed in front of the telescope, which is often a Schmidt camera. Slitless spectroscopy has been used for large stellar surveys.

In the technique of slitlet masks, a picture is usually taken of a region containing several astronomical objects of interest; the exact locations of these objects are determined, and small slits (slitlets) are then milled in the corresponding locations in a metal plate. This plate is substituted for the slit in a conventional spectrograph.

Astronomical Spectroscopy ...contd.

Rather than milling slitlets in a plate, holes may be drilled, which are then plugged with optical fibers. (Such an arrangement is often referred to as a plugboard.) The light is then transported via the fibers to a spectrograph mounted on an optical bench in a laboratorylike environment adjacent to the telescope. Alternatively, robotics may be used to position fibers in the focal plane; the fibers are then anchored to a metal plate via magnets. At the spectrograph, the fibers are arrayed in a line and act as the spectrograph slit. Hundreds of objects can be observed simultaneously, leading to very effective use of the telescope.

Astronomical Spectroscopy ...contd.

Normal spectrographs employ diffraction gratings that are intended to be used in low orders (n $=$ 1, 2, or 3), with colored glass filters used to prevent overlap of adjacent orders. Echelle spectrographs differ from conventional systems in that they employ gratings intended to be used in very high orders (n $>$ 10), resulting in very high resolving power. Normally these orders would fall on top of one another, rendering the data useless. An echelle uses a second dispersal element, usually another grating but sometimes a prism, at right angles to the first, in order to separate the successive spectral strips from each other. A large range of wavelengths can be obtained in the format of nearly parallel segments, well suited for charge-coupled devices.

Astronomical Spectroscopy ...contd.

In integral field spectroscopy, a close-knit bundle of optical fibers is placed in the focal plane and is used to observe an extended astronomical object, such as a gaseous nebula or a galaxy. The light is transmitted via the fibers to a bench-mounted spectrograph. Although the fibers are in a linear array at the spectrograph, their locations in the focal plane are known, and sophisticated data reduction techniques allow the astronomer to reconstruct a spectral image of the object.
Fourier transform spectroscopy is used particularly in the near-infrared. Instead of being dispersed in a spectrograph, the light of a wide band of wavelengths is passed through a Michelson interferometer with variable spacing of its two apertures.

Astronomical Spectroscopy ...contd.

The resulting interferogram, which is an electronic record of the interference signal produced by the interferometer as the separation of the apertures is varied, is converted into a record of intensity versus wavelength by a computer, and is of extremely high spectral resolution.

Application of astronomical spectroscopy extends from solar system objects (the Sun, planets, and comets) to Milky Way objects (stars, including binary stars, ordinary novae, and cataclysmic variables; and gaseous nebulae, such as supernova remnants, H II regions, and planetary nebulae) and to distant galaxies and quasars.

Continuous Spectra

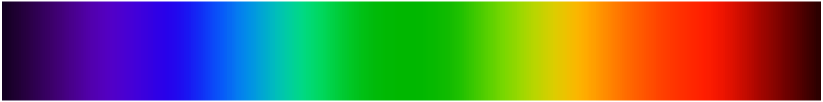

Figure 1: Image of Continuous Spectra

Emission Spectra

Figure 2: Image of Emission Spectra

Absorption Spectra

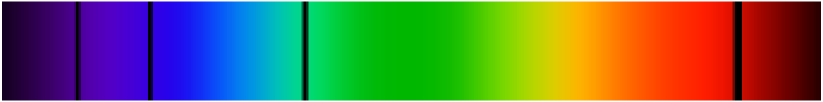

Figure 3: Image of Absorption Spectra

Spectral Environments

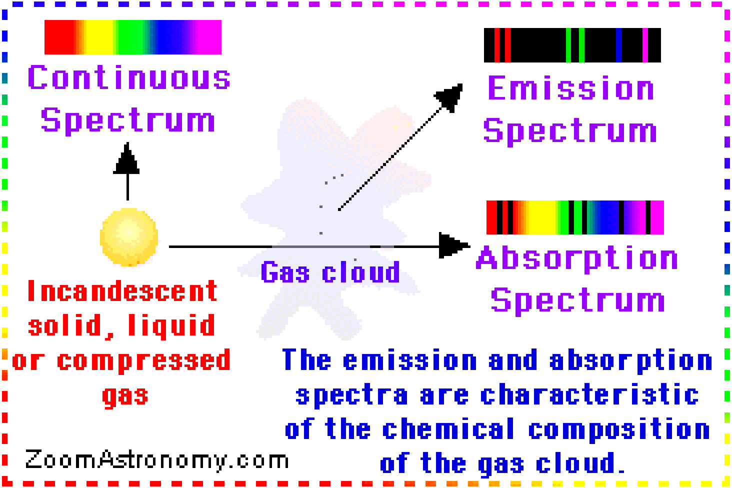

Figure 4: Spectrum Formation in Various Environments

Basic Spectrometer

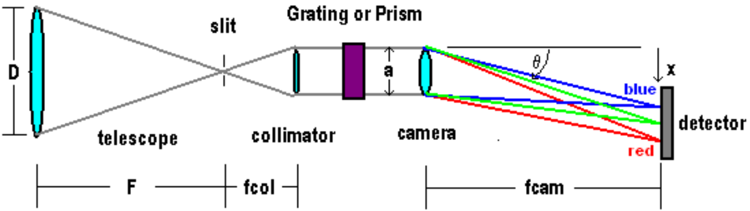

Figure 5: Sketch of a Basic Spectrometer

Telescope & Spectrometer

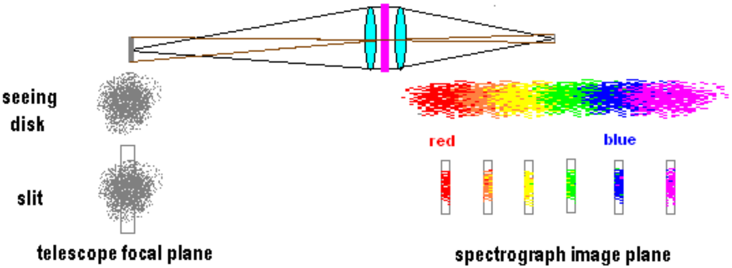

Figure 6: Stellar Spectral Image with a Real Star and a Telescope

Definition of Spectral Resolution

- **Spectral Resolution**$=\mathrm{R} = \boldsymbol{\lambda/\delta\lambda}$
  where λ is the operating wavelength and $\delta\lambda$ is the smallest wavelength interval that can be resolved
- **Photometry** R $<$ 10 for $\delta\lambda \sim 1000\text{Å}$
- **Low Resolution Spectroscopy** (or Narrow Band Photometry) R $<$ 100
- **Medium Resolution Spectroscopy** 100 $<$ R $<$ 10,000
- **High Resolution Spectraoscopy** R $>$ 10,000

Throughput of a Spectrometer

- Luminosity (Etendue in cm^2/steradians) L $= \Omega$A
- **LXR=constant** thus:
- ΩR=const.
- $\Omega \mathrm{R}_{\mathrm{Grating}}$=hA/f
- $\Omega \mathrm{R}_{\mathrm{FP}}$=2$\pi$A thus:
- $\left(\frac{\Omega \mathrm{R}_{\mathrm{FP}}}{\Omega \mathrm{R}_{\mathrm{Grating}}}\right) = \frac{2\pi \mathrm{f}}{\mathrm{h}} \sim 100$
  since $\mathrm{h}_{\mathrm{max}} \sim 5\mathrm{cm}$ & $\mathrm{f}_{\mathrm{max}} \sim 2.5$meter

Spectrometer Throughput ...contd.

- Ω = field of view subtended at the collimator by the aperture/slit
- A = area of the collimator; h = slit height; f = collimator focal length
- Increase slit width $\rightarrow$ more light is accepted $\rightarrow$ but R goes down – vice/versa
- But for some dispersers $\rightarrow$ for same R $\rightarrow$ they can accept more light $\rightarrow$ so more luminous
- LXR of a spectrometer can be fully utilized only when the source region fills the acceptance cone Ω of the spectrometer.
- A spectrometer is always combined with a large telescope to project its acceptance cone Ω as a smaller solid angle ρ onto the sky to match the size of a small region of the source.

Comparison of Grating Spectrometer & Fabry-Perot Spectrometer

Comparable $\rightarrow$	Then for FPS
A$\Leftrightarrow$R	L large
A$\Leftrightarrow$L	R large
A$\Leftrightarrow$L	A small

Table 1: Throughput for Grating & Fabry-Perot Spectrometers

Spectral Lines Criterion

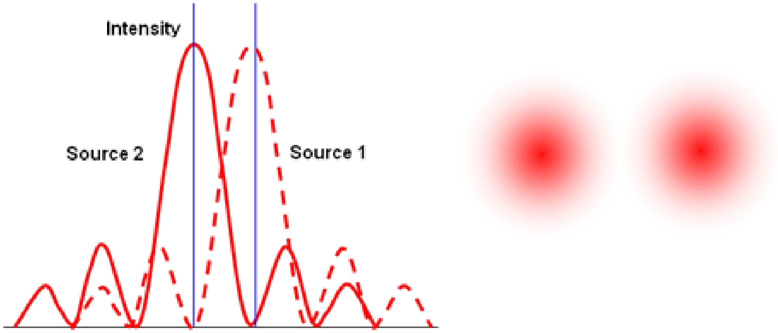

Figure 7: Rayleigh Criterion for Spectral Lines

Disperser Intercomparison

Disperser	Disp. by	Int.Beams of	Range	Resolution
Prism	Refr.	∞	2000Å to 40μm	Low R<500
Grating	Diff.	$10^5 - 10^3$	X-rays to μ wav	Med 500<R<10^4
Interf.	Intf (FP/FTS)	(30/2)	UV to sub-mm	R>10^4

Table 2: Intercomparison of Various Spectrometers

Disperser Intercomparison... contd.

Max. Res. Power	Etendue (same R)	LXR product	Spect.Recov.
R_{max}^{P}	Worst	–	Direct and unambiguous
$R_{max}^{G} \sim 10R_{max}^{P}$	Better	LXR$_{G}$= $(10\text{to}50) \times (LXR_{P})$	Overlapping orders to be sorted
$R_{max}^{Ins} \sim 10R_{max}^{G}$	Best	LXR$_{FP/FTS}$= $(300\text{to}500) \times (LXR_{P})$	Deconv./ Inverse FT

Table 3: Intercomparison of Various Spectrometers

Spectral Line

Spectral lines are the result of interaction between a quantum system (usually atoms, but sometimes molecules or atomic nuclei) and single photons. When a photon has about the right amount of energy to allow a change in the energy state of the system (in the case of an atom this is usually an electron changing orbitals), the photon is absorbed. Then it will be slowly re-emitted, either in the same frequency as the original or in a cascade, where the sum of the energies of the photons emitted will be very different from the energy of the one absorbed. The direction of the new photons will be related to the direction of travel of the original photon.

Spectral Line...contd.

Depending on the type of gas, the photon source and what reaches the detector of the instrument, either an *emission line or an absorption line* will be produced. If the gas is between the photon source and the detector, a decrease in the intensity of light in the frequency of the incident photon will be seen, as the reemitted photons will mostly be in directions different from the original one – this will be an **absorption line**. If the detector sees the gas, but not the original photon source, then the detector will see the photons reemitted in a narrow frequency range – this will be an **emission line**.

Spectral Line Broadening

- Natural Broadening
- Doppler Broadening
- Pressure Broadening
- Rotational Broadening

Spectral Line – Equivalent Width

A measure of the strength of a spectral line. On a plot of intensity against wavelength, a spectral line appears as a curve with a shape defined by the line profile. The equivalent width is the width of a rectangle centered on a spectral line that, on a plot of intensity against wavelength, has the same area as the line.

Equivalent Width

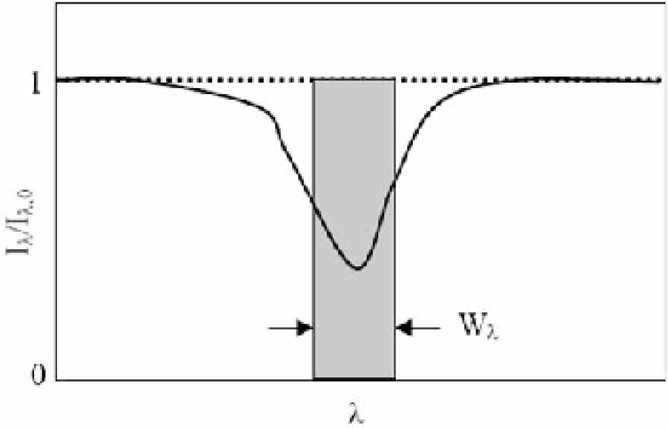

Figure 8: Concept of Equivalent Width

Spectral Line Shapes

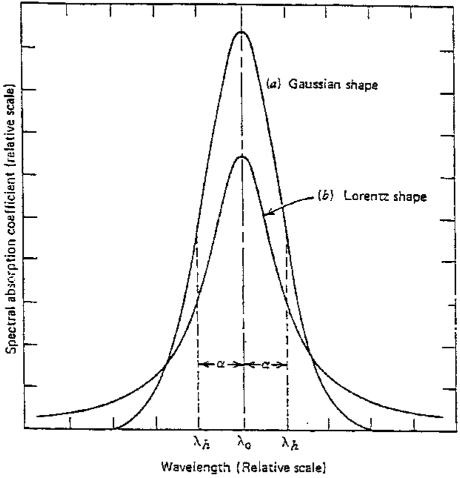

Figure 9: Various Spectral Line Shapes

Natural Broadening

- Line are not very sharp since the energy levels of transition always have a finite width – due to uncertainty principle.
- $\delta\nu_j \sim \frac{1}{(2\pi\tau_j)}$ where $\tau \sim 10^{-6} - 10^{-9}$ secs
- $\Rightarrow$ thus at $\lambda \sim 6000\text{Å}$ $\Rightarrow \delta\lambda_N \sim 0.002\text{Å}$
- **Lorentzian Shape**

Doppler Effect: Shift & Broadening

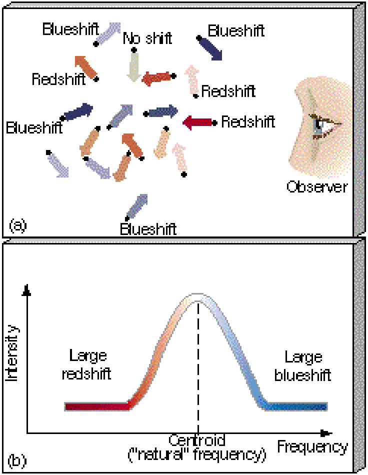

Figure 10: Concept of Doppler Broadening

Doppler Broadening

- Doppler Width – due to random motion of atoms in a heated vapour
- $\delta\lambda_{\rm D} = 7.16 \times 10^{-7} \lambda_0 \sqrt{\frac{\rm T}{\rm M}}$
- where M=Mass no. of emitting species; T=Temperature at thermal equilibrium and λ_0= line center wavelength
- $\sim 0.03 \text{Å}$ at T$\sim$ 5700°K for Iron (Fe)
- **Gaussian Shape**

Zeeman Effect

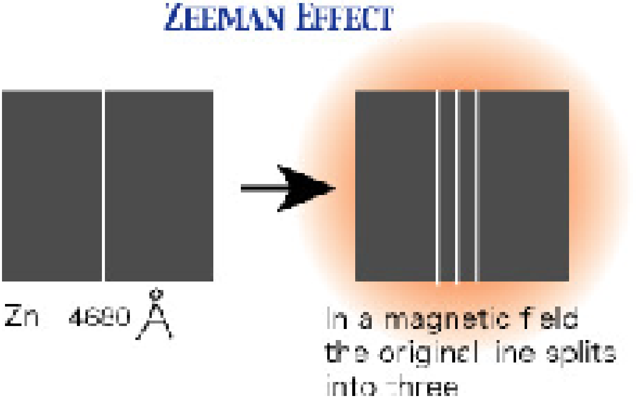

Figure 11: Zeeman Splitting of Spectral Lines

Zeeman Effect ...contd.

- Splits the spectral line under influence of strong magnetic fields
- $\delta\lambda_{\mathrm{B}}$ (in nm) $=$ $4.2 \times 10^{-3}(\mathrm{g}/2.5)(\lambda(\mathrm{nm})/(600))^2(\mathrm{B(G)}/1000)$ where g is Lande's g factor.
- Splits are $\sim 0.1 - 0.6\text{Å}$ @ 600nm
- Usually Ap stars show spectral line splits which can have magnetic fields of the order 1kG to 30KG

Rotational Broadening

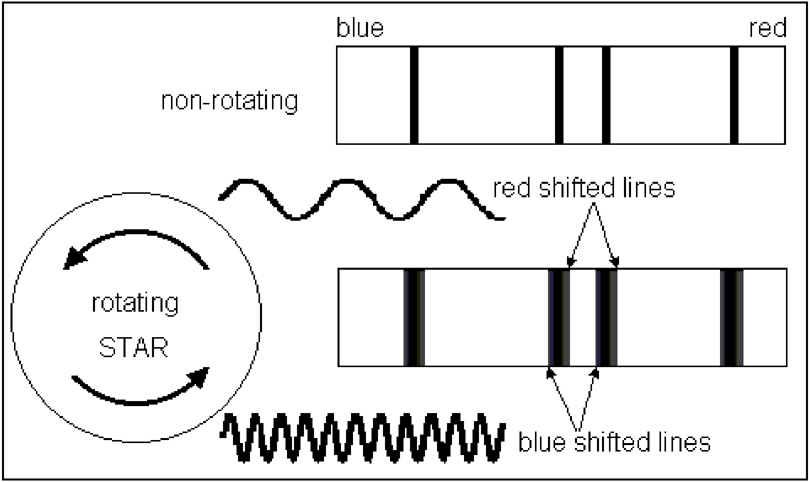

Figure 12: Rotational Broadening of Spectral Lines

Grating Spectrometer

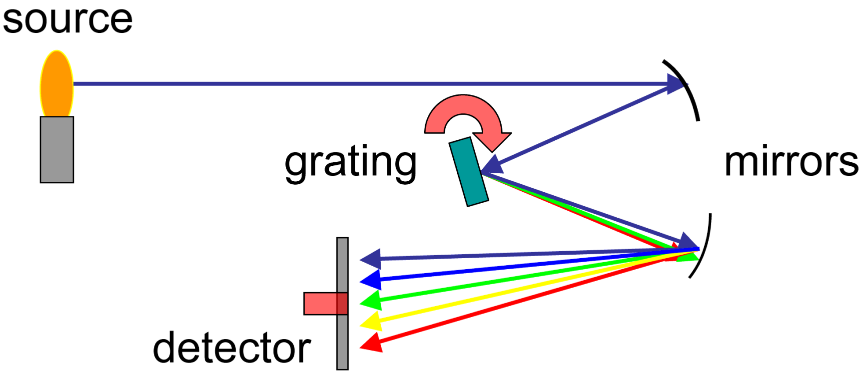

Figure 13: Sketch of Grating Spectrometer

Spectroscopy Definitions

- **Disperser** Separates different wavelengths by spatially spreading them out
- **Dispersion** Measure of spreading
- **Angular Dispersion** $\mathrm{d}\theta/\mathrm{d}\lambda$
- **Linear Dispersion** Linear Dispersion of two images in the focal plane of the camera lens of focal length f $\rightarrow$ $\mathrm{dl}/\mathrm{d}\lambda = \mathrm{f}(\mathrm{d}\theta/\mathrm{d}\lambda)$
- **Reciprocal Dispersion** dλ/dl in units of Å/mm or nm/mm

Blazed Grating

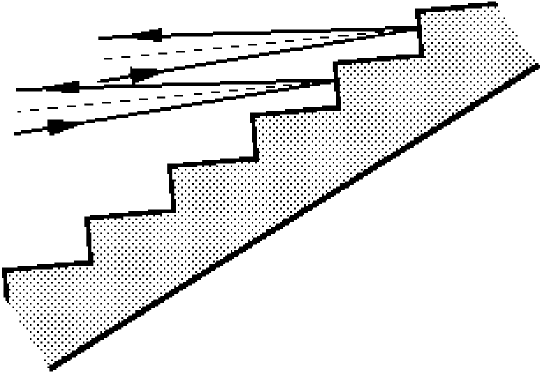

Figure 14: Sketch of Blazed Grating

Blazed Grating...contd.

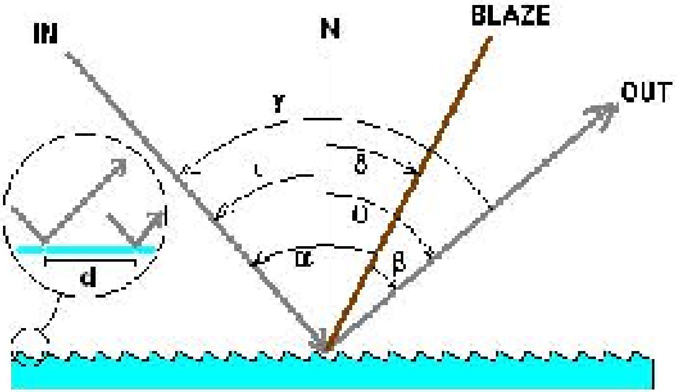

Figure 15: Angles involved in Blazed Grating Spectrometer

Grating Orders

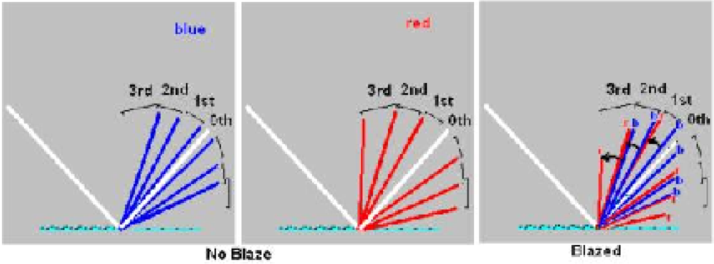

Figure 16: Orders in Blazed and un-Blazed Gratings

Blazed Grating...contd.

The grooves of a blazed grating are shaped as steps. One side of these steps is mirroring, so that the incident beam will be reflected optimally back in the desired direction. The further the outfalling beam is away from this optimized direction, the weaker the beam will be.
In a given diffraction direction only certain wavelengths are reflected: those wavelengths for which the path difference from adjacent steps is an integer multiple m of the wavelength. The number m is called diffraction order. The grating equation applies to a given diffration direction (λ = wavelength): m x λ = const.

Echelle Spectrometer

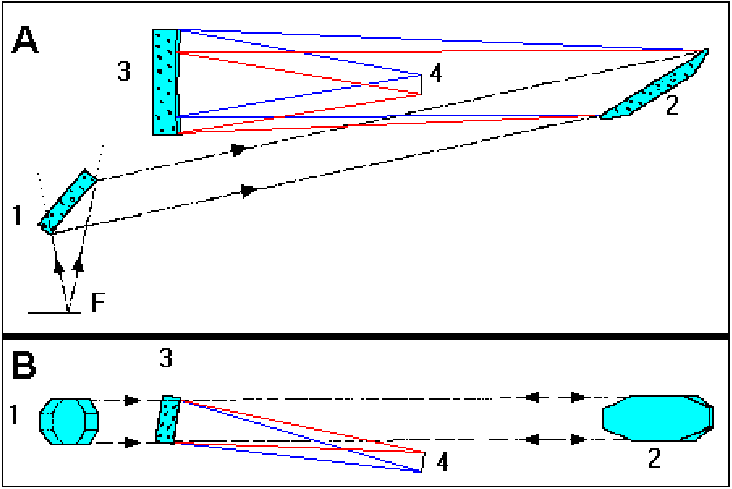

Figure 17: Sketch of Echelle Spectrometer

Echelle Spectrometer ...contd.

A = side view; B = top view; red = long-wavelength side; blue = short-wavelength side
F = focus of the main mirror and entrance diaphragm of the spectrometers
1 = collimator mirror: the collimator mirror produces a parallel beam
2 = Echelle grating: the Echelle grating has 316 lines per millimeter and is used in orders 40 to 61. The Echelle grating is a blazed grating, i.e. the grooves are shaped as steps and the front sides of these steps have a reflecting coating, so that the reflected intensity of the grating is optimized for the desired reflection direction.

Echelle Spectrometer ...contd.

3 = cross disperser grating: The cross disperser grating has 1200 lines per millimeter, it is also a spherical mirror which focusses the parallel beam onto the detector. The grooves are perpendicular to those of the Echelle grating. Thus the individual orders of the Echelle grating are separated and are mapped one below each other.
4 = Echelle detector: The detector is a high sensitivity, photon counting and imaging detector with a sensitive area of 40mm x 40mm. It is capable of detecting up to 30.000 photons per second. The spectral resolution of the Echelle spectrometer is 104, i.e. at a wavelength of 100 nm one resolution element has a width of 0.01 nm. The Echelle spectrum covers a wavelength range from 90 nm to 140 nm in the Echelle orders 40 to 61.

Echelle Spectra of Sun

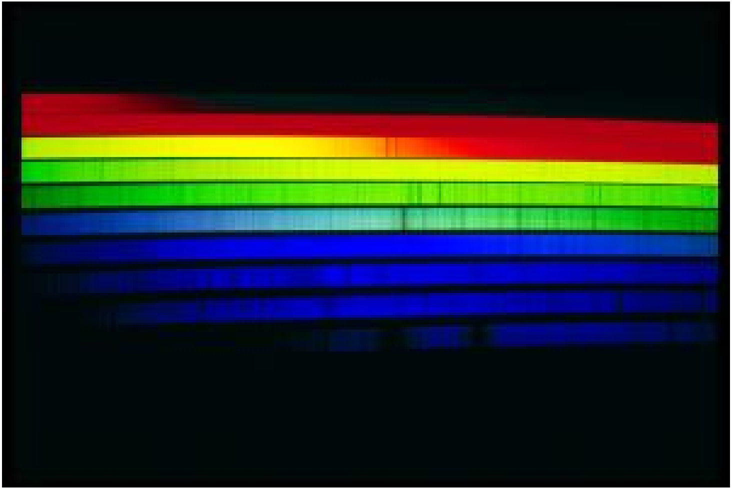

Figure 18: Sun's Echelle Spectra

Grating Design

- A 50mm wide grating is used in a 1/4 meter monochromator with 1200 lines/mm & blazed at 500nm in the Ist order with a diffraction angle at 17.5°.
- Find (i) the reciprocal linear dispersion (ii) the theoretical resolution and (iii) actual resolution for a $25\mu m$ slit.
- Pitch=p=1200l/mm=1/a (where a=groove spacing)
- $\lambda_{\rm Blaze}$=500nm=λ_0; n=order=1; W=50 mm
- Focal length=f=1/4meter=250mm; $\beta = 17.5^\circ$

Grating Design...contd.

- (i) Angular Dispersion=dβ/dλ=n/(a cosβ)
  Linear Dispersion=(f/10^6)dβ/dλ(nm/mm)
  Reciprocal Linear Dispersion=$\mathrm{d}\lambda/\mathrm{dl} = \frac{10^6 \mathrm{a} \cos\beta}{\mathrm{fn}}$
  $= \frac{10^6 \cos\beta}{\mathrm{fnp}} = \frac{10^6 \cos 17.3^\circ}{250 \times 1 \times 1200}$
  =**3.2nm/mm**
- (ii) Theoretical Resolution
  $= \mathrm{R_{Th}} = \lambda_0/\mathrm{d}\lambda = \mathrm{Wn/a} = \frac{50 \times 1}{1/1200}$
  $\mathbf{R_{Th} = 60,000}$

Grating Design...contd.

- (iii) For a 25μm wide slit $\delta\lambda$=Slit Width X Reciprocal Linear Dispersion =(25mm/1000) X 3.2(nm/mm)=0.08nm
  $\mathbf{R_{actual}}$=$\lambda_0/\delta\lambda$ = $500/0.08$=**6250** (much less than R$_{\mathrm{Th}}$ $\sim 60,000$)
  Usual measured values for such monochromator $\mathbf{\sim 0.09nm(\sim 1\text{Å})}$

Grating Formulae

- **Blazed Gratings** n$\lambda_{\rm blaze}$=2asin$\theta_{\rm blaze}$ If blazed for Ist order (n=1) at λ then also blazed for IInd order (n=2) at $\lambda/2$ – and so on
- **Dispersion** dβ/dλ=n/(acosβ) where n=order; a=ruling gap; W=width of the grating; N=total no. of rulings
  Effective aperture for the diffracted beams=a$_{\rm p}$=Wcosβ
- **Resolution** R=a$_{\rm p}$ dβ/dλ=Wcosβ(n/(acosβ))=Wn/a=Nn
- **Free Spectral Range**=FSR=1/(λn)=1/(2t) where t=width of each ruling

Overlapping Orders

- IIIrd Order (n=3) at λ; IInd Order (n=2) at $(3/2)\lambda$; Ist Order (n=1) at 3λ; All would coincide with each other
- Prisms/small gratings/color filters are used in front of the slit for order sorting (pre-dispersing)
- Overlapping in useful since it acts as reference line when standards do not exist
- Conventional grating for VIS/UV – 1200 lines/mm; W $\sim$ 20cm; Thus N=20X10X1200=240,000
- In IInd order R=480,000 (Theoretical); Actually a few 100,000 i.e. R$\sim 10^5$ is easily realizable

Normal versus Echelle Grating

Grating Type	Blaze angle δ	lines/mm	order	R^{Th}_{max}
Normal	$\sim 20^\circ$	high$\sim$1200	low n=2	$5X10^5$
Echelle	$\sim 60^\circ$	low$\sim$200	high n=100	10^6

Table 4: Comparison of Normal & Echelle Grating parameters

Note – Echelles have widely spaced rulings.
For Echelles – FSR $\sim$ few tens of Å in visible – so overlapping problem is very severe
For faint sources, to accept all light from the seeing disk, echelles of large ruling length and large total width are required for high resolution (more than R$\sim 10^5$) and thus impractical. For this domain of resolution, interferometers and crossed spectrometers are useful.

Coude Feed 0.9-meter Telescope

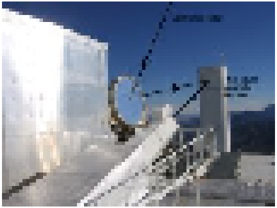

Figure 19: Coude Feed 0.9-meter Telescope

Coude Feed Spectrograph

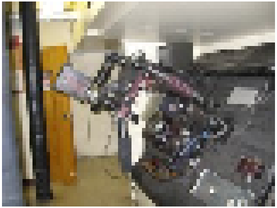

Figure 20: Coude Feed Spectrograph

CCD Dewar

Figure 21: Coude Feed CCD Dewar

CFLIB Spectra

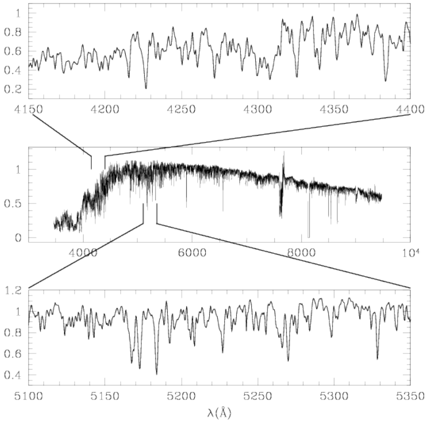

Figure 22: High Resolution CFLIB Spectra from INDO-US Spectral Library – one of approx. 1200 spectra from CFLIB

Fabry-Perot Spectrometer (FPS)

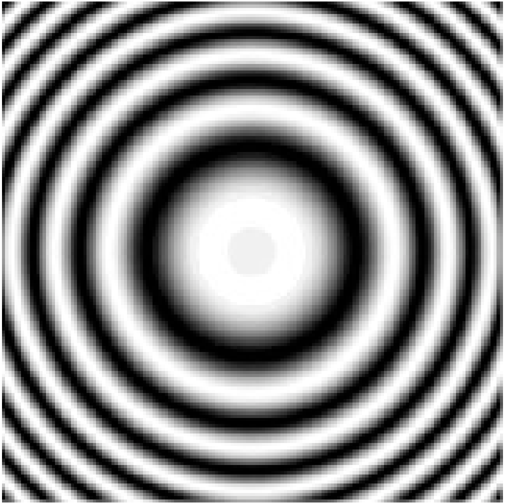

Figure 23: Image of FPS Rings

FPS...contd.

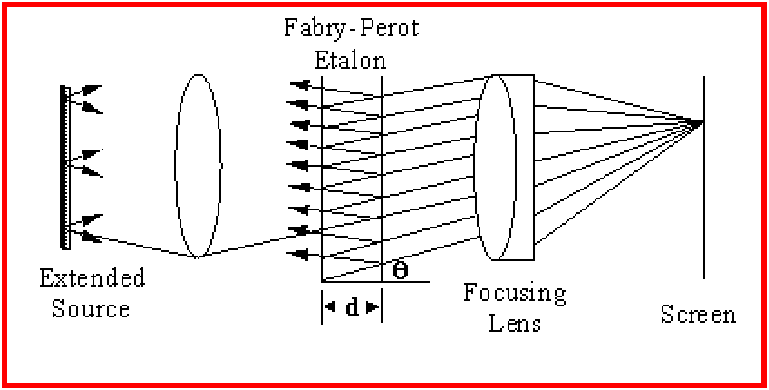

Figure 24: FPS Interference Concept

FPS Theory

- **Basic FP equation** for constructive interference:
  $\mathbf{n\lambda = 2\mu t cos\theta}$
  where n=order of interference; μ=refractive index of medium; t=geometric spacing; θ=angle of incidence
- **Free Spectral Range (FSR)**=$\Delta\sigma_{\mathrm{FSR}} = 1/(2\mu\mathrm{t})$
- **Wavelength λ Scanning methods:**
  Vary μ – by varying pressure of medium (pressure scanning)
  Vary t – spacer (peizo based) scanning
  Vary θ – non-linear

Reflective Finesse

- **Reflective Finesse**$=\mathrm{N_R}=\frac{\pi\sqrt{\mathrm{R}}}{(1-\mathrm{R})}$
- **Airy Function:**
  $\mathrm{AI}(\sigma) = \mathrm{AI}(\sigma_0)\frac{(1-\mathrm{R}-\mathrm{A})^2}{(1-2\mathrm{R}\cos(\mathrm{x})+\mathrm{R}^2)}$
  where x$=4\pi\mu\mathrm{t}(\sigma - \sigma_0)$ and $\sigma = 1/\lambda$
  AI(σ)=Intensity at wavenumber σ
  AI(σ_0)=Peak Intensity at line center wavenumber σ_0
  R = Reflectivity of plates and A = Absorption of coatings; FWHM = Full Width at Half Maximum; d = aperture diameter; f = focal length of objective lens

FPS...contd.

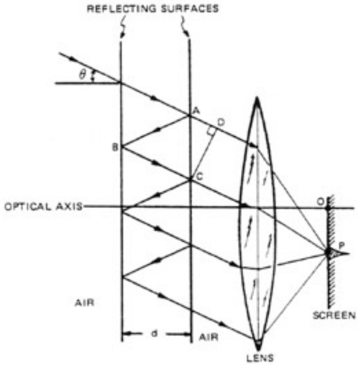

Figure 25: FPS Interference Concept

AIRY Function

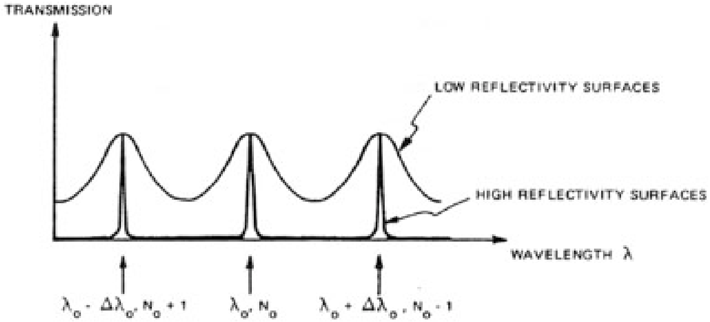

Figure 26: AIRY Function plot

- **Spherical Defect Finesse**=N_{Sph}=m/2
  for λ/m plates
  Rectangular Function:
  PD(x)=$(\Delta\sigma_{FSR}\Pi(x))/(4\pi d_f)$
  where:
  $\Pi(x)$=1 for $(2\pi d_f)/(\Delta\sigma_{FSR}) > |x|$
  $\Pi(x)$=1/2 for $(2\pi d_f)/(\Delta\sigma_{FSR}) = |x|$
  $\Pi(x)$=0 for $(2\pi d_f)/(\Delta\sigma_{FSR}) < |x|$
  and
  $d_f=\frac{\Delta\sigma_{FSR}}{2N_{Sph}}$
  and
  $FWHM = 2d_f$

Mis-Alignment Defect Function

- **Mis-alignment Finesse**=N_{Mis}=$K_{\mathrm{p}}/\sqrt{3}$
  for λ/K_p plates
  Inverse Parabolic Function:
  Mis(x)=$(1 - \mathrm{x/P})^{1/2}$
  where $\mathrm{P} = 2\pi\mu/\mathrm{K_p}$
  Ref: Appl. Opt., **30**, Feb. 1, pp 373 (1991)

Micro-Smoothness Defect Function

- **Micro-smoothness Finesse**$=\mathsf{N}_{\mathrm{Mic}}=\mathsf{K}_{\mathrm{g}}/4.7$
  for λ/K_g plates
  Gaussian Function:
  $\mathrm{Mic(x)}=(\mathrm{D}/\sqrt{\pi})\exp(-\mathrm{x}^2\mathrm{D}^2)$
  where $\mathrm{D} = \Delta\sigma_{\mathrm{FSR}}\sqrt{\frac{\ln 2}{2\pi \mathrm{d_g}}}$
  and
  $\mathrm{FWHM} = 2\mathrm{d_g}$

Aperture Defect Function

- **Aperture Finesse**=$\mathrm{N_{Ap}}=\Delta\sigma_{\mathrm{FSR}}/(\mathrm{FWHM})$
  Rectangular Function:
  AP(x)=$(\Delta\sigma_{\mathrm{FSR}}\Pi(\mathrm{x}))/(4\pi \mathrm{d_f})$
  where:
  $\Pi(\mathrm{x})$=1 for $(2\pi \mathrm{d_f})/(\Delta\sigma_{\mathrm{FSR}}) > |\mathrm{x}|$
  $\Pi(\mathrm{x})$=1/2 for $(2\pi \mathrm{d_f})/(\Delta\sigma_{\mathrm{FSR}}) = |\mathrm{x}|$
  $\Pi(\mathrm{x})$=0 for $(2\pi \mathrm{d_f})/(\Delta\sigma_{\mathrm{FSR}}) < |\mathrm{x}|$
  FWHM=$2\mathrm{d_f} = \frac{\sigma_0 \mathrm{d}^2}{8\mathrm{f}^2}$

Instrument Profile

- **I = AI * PD * MIS * MIC * AP**
  where '*' represents convolution operation as:
  h(k)=x(k) * y(k)=$\int_{-\infty}^{\infty} x(k-n)y(n)dn$
  where h is the resultant convolved output of the two input functions (x and y)
- **RECORDED/OBSERVED SPECTRUM(O) =SOURCE PROFILE(S) * INSTRUMENT PROFILE(I)**

Instrument Profile...contd.

- **O=S*I**
  where O is the observed/recorded profile
  S is the source profile
  I is the Instrument profile
- S $= \mathrm{F}^{-1}[\frac{\mathrm{F(O)}}{\mathrm{F(I)}}]$
  where F is Fourier Transform of the function

IC Optical ET100 FPS

Figure 27: IC Optical ET100 FPS Photo

Observational Planning

- List of Program Objects (with accessible RA/DEC for that latitude)
- List of Standard Stars (with accessible RA/DEC for that latitude)
- The Standard Stars should cover bright, faint & various spectral types
- Grating/Grism settings – Resolution and wavelength range, slit width and blocking filters selection
- Spectral lamp selection

Observational Planning

- Take spectral lamp spectra
- Take Halogen lamp spectra
- Observe Standard star
- Observe Required Object
- Use IRAF-DOSLIT procedure for date reduction

HeNe Lamp Spectra

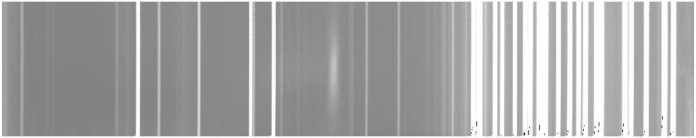

Figure 28: Example of a He-Ne Lamp Spectra used for wavelength axis calibration

Halogen Lamp Continuum Spectra

Figure 29: Example of a Halogen Lamp Spectra used for overall instrument sensitivity determination

Standard Star Spectra

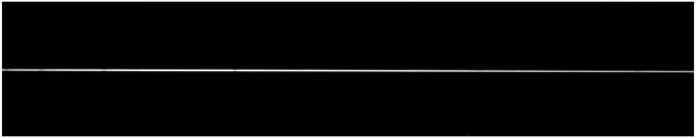

Figure 30: Example of a Standard Star Spectra used for flux calibration

Object – Supernova Spectra

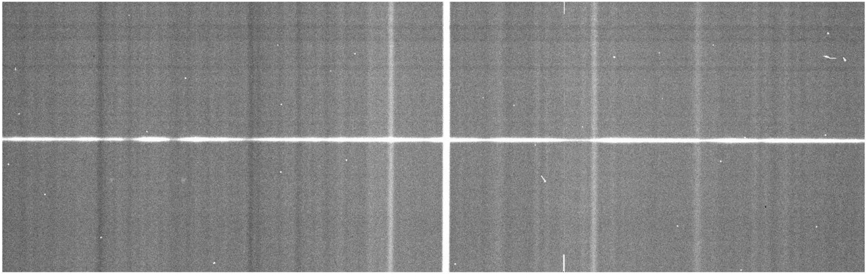

Figure 31: Example of a Target Object – Supernova Spectra

Reduced HeNe Lamp Spectra

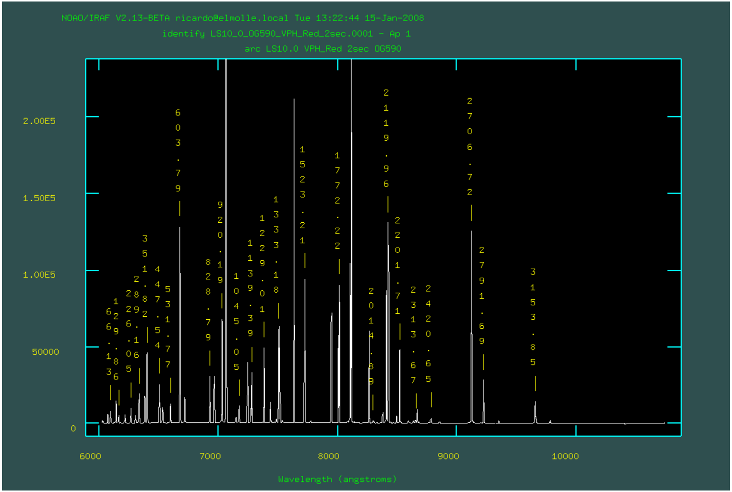

Figure 32: HeNe Lamp Spectra reduced with wavlength calibrated axis

Sensitivity Function

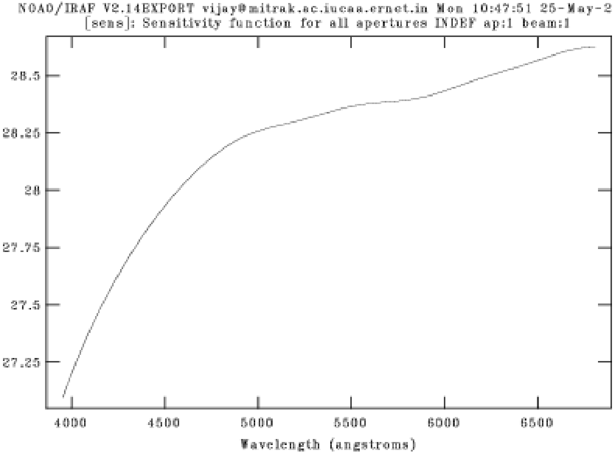

Figure 33: Plot of Sensitivity Function

Reduced Standard Spectra

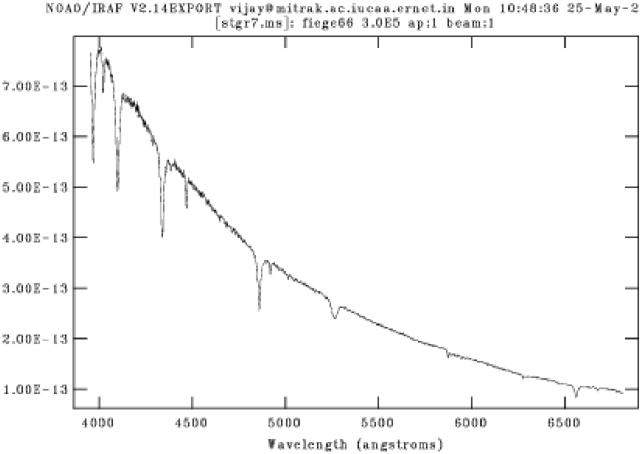

Figure 34: Plot of the Reduced Standard Star Spectra

Reduced Target Object Spectra

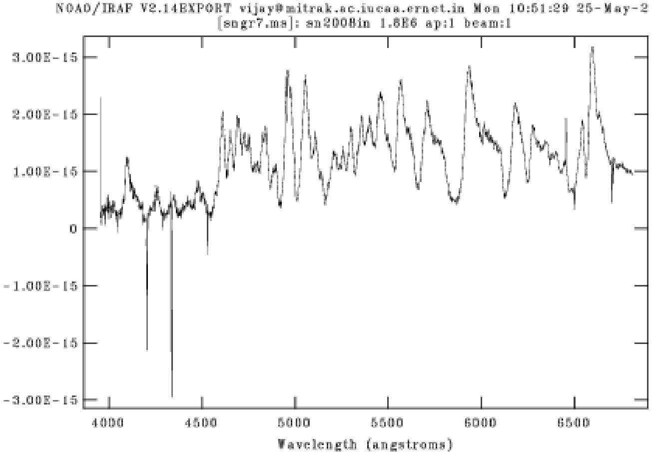

Figure 35: Plot of the Reduced Target Object – Supernova Spectra

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Thanks