Introduction to Spectroscopic Techniques
(low dispersion)

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• Basic optics of gratings and spectrographs (with emphasis on long-slit spectroscopy)
• Observing steps, and data-reduction
• Other types of spectrographs, and future instrumentation of large telescopes
Principles of gratings (1)

- Grating needs to be illuminated in // beam
- Hence a collimator C and an objective O
- \( \sin \theta_2 - \sin \theta_1 = n k \lambda \) (k: order; n: grooves/mm)
- Intrinsic resolution: \( \bar{R}_0 = n k L \) (L size of grating)
  (by definition: \( R = \lambda/\Delta \lambda \), with \( \Delta \lambda \) the smallest resolvable element)
Principles of gratings (2)

- \( a = L \cos \theta \) (\( a \): size of exit beam = \( \Phi \) of camera)

- To \( \tilde{R}_0 \) corresponds an exit size (for an infinitely small entrance slit) \( d_0 = f \lambda/a \) (\( f \): focal length of the camera; diffraction limit of element of size \( a \))

- To be resolved, we need \( d_0 > 2 \) pixels, that is:
  \[
  f/a > 2 \frac{X}{\lambda} \\
  \text{With } X = \sim 25 \mu \text{ and } \lambda \sim 0.5 \mu, \text{ this gives:} \\
  f/a > 50
  \]
  Camera not open enough! (luminosity)

  Conversely, if one wants \( f/a \sim 3 \), one needs \( X = \sim 1 \mu \)
  (remember, pixel was much smaller, \( \sim 3 \mu \), in photography!)

- Thus will use \( d > d_0 \), i.e. not use full resolution of grating

- The exit image is optically conjugated to the entrance slit of size \( l_0 \)!
Match of spectrograph to telescope (1)

But entrance slit needs also to be matched to telescope and seeing, and opened to increase light throughput.

If you open the entrance slit, you degrade the spectral resolution, i.e.
one gets \( R < \bar{R}_0 : \bar{R} = \bar{R}_0 \frac{d_0}{d} \)

In addition, one can use a reduction factor in the spectrograph: \( \frac{d_{\text{exit}}}{l_{\text{entrance}}} < 1 \), (typically 1/6) to minimise size of optics.
Compromise with spectrographs

- If equal weight given to $\tilde{R}$ and $\mathcal{L}$, best choice is for $l/d_0 = 1$ (but then camera not open enough...)
- In astronomy, preference given to $\mathcal{L}$, so intrinsic resolution is not used.
Match of spectrograph to telescope (2)

- In the focal plane of telescope D, you need:
  - \( l = D \, m_T \, \alpha \) (\( \alpha \) seeing angle)
- Thus \( \breve{\mathcal{R}} = \breve{\mathcal{R}}_0 \, d_0 /d = \breve{\mathcal{R}}_0 \, f \lambda /a \cdot 1/d \sim \breve{\mathcal{R}}_0 \, \lambda /\alpha \cdot 1/D \)
  
  that is for a given \( \breve{\mathcal{R}} \), the size of the grating (which governs \( \breve{\mathcal{R}}_0 \) ) is proportional to \( D \)!

  This is a problem for large telescopes!

- Full formula is:
  \[
  \breve{\mathcal{R}}\alpha = 2 \, L/D \, \tan \beta \left[ \cos \theta_2 / \cos \theta_1 \right] \text{(anamorphism)}
  \]

  \( \breve{\mathcal{R}}\alpha \) is the « efficiency » of the system
  - \( \beta \) blaze \( \sim \theta_2 \) « R2 » grating: \( \tan \beta = 2 \) (63°)
  - « R4 » grating: \( \tan \beta = 4 \) (75°)
**Application: VLT**

### Photon-starved Mode
- D = 8 m Telescope diameter
- 0.5 μm seeing = 0''.65-median; 0''.3-10%
- p = 12 μm (4k)² V/NIR pixels (market)
- F/ω Camera: ω ≥ 1.4; L ≥ 80 mm (optics)
  \[ \alpha_{\text{sky}} = 0''.44 \text{ (2-pixel sampling)} \]

**Grating diameter L; on-sky slit width α**

\[ R_\alpha = \lambda / \delta \lambda = 2(L/D) \tan \varphi \]

- L = 80 mm; tan \( \varphi = 1 \) \[ R_\lambda = 4.10^3 \text{ (FORS)} \]
- L = 200 mm; tan \( \varphi = 4 \) \[ R_\lambda = 4.10^4 \text{ (UVES)} \]

**image slicers not always required**
Order superposition

- At given $\theta_2$ (i.e. on given pixel of detector), $k\lambda = \text{cste}$

\[
\begin{array}{cccccc}
& 4000 & 6000 & 8000 & 10000 & 12000 \text{ Å} \\
\hline
k=1 & | & | & | & | & > \lambda \\
\hline
k=2 & |---|---|---|---|---|----|>
\end{array}
\]

E.g. first order red is superposed by 2. order blue.

- Use of filters to separate orders (high-pass red (cuting the blue) in the above example)

- If one wants higher dispersion, go to higher orders (e.g. $k \sim 100$). But overlap of orders then unavoidable ($\lambda$ shift between orders too small to use filters as separators), so one needs cross-dispersion to separate orders.
Echelle spectroscopy

Compromise between resolution, detector size, ....

(here Hamilton spectr. at Lick)

Wavelength \rightarrow \text{Spatial direction}

\ldots and order spacing, for sky or background subtraction

(here HIRES at Keck)
Slit losses

- A rectangular slit does not let through all energy from a circular seeing disk! (but is better than circular aperture)
- For standard stars observations, open wide the slit if you want absolute photometry!

![Energy passed by an aperture for a Gaussian point spread function of FWHM : W](image)
Differential refraction

• $\Delta R(\lambda) = R(\lambda) - R(5000\text{Å}) \sim \text{cste} \left[ n(\lambda) - n(5000) \right] \tan z$
  Ex: for $AM = 1.5$, $\lambda=4000$ Å, $\Delta R \sim 0.70''$ : relative loss of flux
  Depends on $P$ and $T$ (altitude) and humidity
  Worse in the blue, negligible in the near-IR

• Use parallactic angle for slit (oriented along the refraction)
  (see diagram, after Filippenko, PASP, 1982)

Venus (from J. Zhu)
Blazed gratings

- Blaze angle ($\delta$) chosen such that max. of interferences coincides with max. of diffraction in the selected order
- Some shadowing occurs at large incidence angles, reducing a bit the efficiency

Fig. 14. Geometry of groove shadowing: (a) blaze of an inside spectral order, (b) blaze of an outside spectral order. Shadow factors derived from these geometries may be used to accurately determine the blaze efficiency.
• Blazed gratings are efficient close to blaze angle
• Choose grating according to wished wavelength range
• Keeping in mind that efficiency drops sharply bluewards of blaze, but slowly redwards of it: thus blaze $\lambda$ should be bluewards of your wished central wavelength !!
Flat Field correction

- To correct the high spatial-frequency variations across the image/spectrum
- Origin of variations: pixel to pixel sensitivity variations (detector); transmission variations of optics (or dust particles…)
  - It is a multiplicative or « gain » effect
- Illuminate with a uniform (« flat ») source and use the same optical path as the astronomical source….Difficult because at infinity!
- Need a high S/N not to degrade the science exp.
- Dome flats or internal calibration lamps not at infinity…correction approximate but flux OK
- Sky flats better, but not possible in spectroscopy (not enough signal), only for imaging
- There is an extra additive component due to night sky (emission lines) fringes…. 
Flat Field correction (2)

- FF is wavelength dependant: to be done through whole spectrograph
- Needs to be normalised to 1 to conserve fluxes
- One can correct vigneting along the slit length if FF illumination is correct (usually not the case with dome flats)
Sky emission

(from Massey et al. 1990)

• Sky is bright, specially in near-IR !!
• Needs to be subtracted
• Requires a linear detector
Importance of sky subtraction

Example of a $V=16.5$ QSO in the far-red
(that is almost as bright as the full moon…)

Obtained with the ESO 3.6m and Reticon diode array
Top: full spectrum    Bottom: sky subtracted

The important features (broad Balmer lines) are completely hidden in the OH night sky lines…
Becoming worse when going to the near-IR (J, H, K bands)
Atmospheric absorptions from Vreux, Dennefeld & Andrillat (1983)

- Due to $O_2$ (A, B, ..) and $H_2O$ (a, Z, ..) in the visible, plus $CO_2$, $CH_4$, etc… in the near-IR
- Not to confuse with stellar absorption bands…
- To correct: needs to observe a hot star (no intrinsic absorption lines) in the same conditions (similar airmass) and divide the object’s spectrum by the hot star’s spectrum. Saturated lines (A,…) are difficult to correct completely.
- The A, B, notation comes from Fraunhoffer (1814, solar spectrum)
Standard stars (1)

Example from Baldwin & Stone (1984)

Choose Standard with appropriate Spectral Energy Distribution
With as few absorption lines as possible
WD’s are ideal, but faint…
Standard stars (2)

Check that:

- The sampling is appropriate
- The wavelength range covers your needs (careful in the far-red...!)

In contrast to our earlier results, we emphasize that all of the STT/CCD points are now interpolated. The elimination of any extrapolation should significantly improve the accuracy of the calibration in the region 3A 7760–8290.

For completeness, Table I includes the previous scanner results for 33 6056 and 6790. The new scanner observations have been combined with the old ones where they overlapped at 3.750. Generally the agreement between the two data sets was excellent, so those values are little changed.

For the three stars which are faintest in the red our results do not extend all the way to 3.10 600. In addition, the two longest wavelength points were discarded for two other stars because of excessively large internal errors.

Fig. 1 shows spectra of the 10 new standards and of nine standard stars from the list of Stone (1977). The observations were made with the CTIO STT-Vidicon systems and with the...
Wavelength calibration

- This image is a raw (He + Ar) exposure
- You may need to saturate some of the lines…
- 2D wavelength calibration (line by line) will also correct the distortion
- If CCD well aligned, 1D calibration may be enough
First identify some lines, then mostly automatic
Wavelength calibration (3)

Plot residuals
Eliminate outstanding lines
Recalculate calibration

Plot delta’s
If necessary, adjust degree of polynomial (depending on instrument: 2d OK most of the time, but special cases e.g. image tubes have S distorsion, hence 3d degree preferable)
One needs to understand the origin of the shape (grating curve, detector’s response, etc..) before deciding fitting method (poly, spline) and smoothing parameter.

Assumes FF has removed small scale features
Try to have more than one Std star observed (odd number if possible)…
Extraction of spectrum

- Assumes Offset and FlatField corrected
- 2D wavelength calibration (corrects distortion)
- See if vignetting (transmission changes along the slit); can be corrected by the FF
- Cosmic rays removal
- Simple sum, or weighted sum of object lines
- Sky subtraction (average on both sides of object)
Summary of operations

\[ S_\star (\text{ADU}) = G_{x,y} F_\star \cdot t + O_f \quad (\text{Dark current negligible}) \]
\[ S_{FF} = G_{x,y} F_{FF} \cdot t' + O_f \]

- Do \[ F_\star /F_{FF} = \frac{(S_\star - O_f)}{(S_{FF} - O_f)} \cdot t'/t \]
and same for Standard star
- Cosmic rays correction
- Wavelength calibration
- Extraction of spectrum (with sky subtraction)
- Extinction correction
- Division by the response curve

final spectrum in absolute units
Focal Reducer

- Spectrograph is ‘straightened’ out, thus grating works in transmission instead of reflection.
- Field of view (2θ) defined by field lens:
  \[ D_{FL} = 2f_T \theta = 2f_c \alpha \]
  Final focal length \[ f' = m'_\text{cam} D_T \]
  Reduction factor is \[ m_{\text{Tel}} / m'_\text{cam} \]
  To keep exit rays ‘on axis’, one adds a lens or a prism to the grating: grens, or grism!
Focal reducer (2)

- Parallel beam: can introduce filters (in particular interference filters), gratings, Fabry-Perot’s, polarimeters, etc…
- Very versatile instrument
- Entrance plate (telescope focal plane) versatile too
- Exemple of FORS/VLT (with slits or masks)
Slits, or masks?

19 slits, fixed length

~30 slits, variable length
Exemple of multi-objects (slits)

Field of view: ~ 7’

The wavelength range depends on the position of the target in the field!
Multi-objects (masks)

For larger fields of view:
**Vimos**: several quadrants, with independant optics and cameras (gaps in the field!)

Two quadrants, with about 100 slits in each mask
Spectroscopic modes

Note: also slit-less spectroscopy (objective prism or grism)
Integral field spectroscopy

Two dimensional original on-sky image

Optical slicing of the on-sky image

Spectral dispersion of the sliced image

Computer reconstruction of the 3D data cube

Spectrum of each 2D pixel

Spatial in X  Spatial in Y  Spectral Dimension

Computer reconstructed image
3D Spectroscopy (principle)

1. Sample object in spatial elements

2. Re-arrange spaxels to slit and feed light to spectrograph

3a. Extract spectra

3b. Reconstruction of narrow- & broad-band images

340 nm - 950 nm
• Image slicer retains spatial information within each slice. Is used also for stellar spectroscopy with high-resolution (e.g. 1.52m at OHP)

• FOV limited because total number of pixels in detector is limited (must contain \( x \), \( y \), \( z \))
Different modes (2)

Wide field: fibers
(here 2dF)
Discontinued sampling
(Medusa mode)

Continued sampling:
IFU with lenslets
Small field of view
(a few ‘)
Limited by total number
of pixels in detector
(X x Y x \lambda)
Combination: FLAMES-IF

FLAMES (d-IFUs)

• 15 deployable IFUs
• FLAMES (d-IFUs)
• 20 μ-lenses (2”x3” field)
• 0.37-0.95 μm range
• ℜ ~ 1.1x10⁴
• λ/Δλ = 9.5; ε_F ~ 70%

FLAMES (Argus)

• single IFU spectroscopy
• 308 μ-lenses (12”x7” field)
• 0.37-0.95 μm range
• ℜ ~ 1.1x10⁴
• λ/Δλ = 9.5; ε_F ~ 70%

η Carinae

deployable IF heads
Example of Galex + Vimos: **needs flux calibration to connect!!**

Starburst in the Chandra Deep Field South observed by GALEX in UltraViolet and by VIMOS (http://cencosw.oamp.fr/)

A clear Lyman $\alpha$ emission is detected in the spectrum of this galaxy at a redshift $z = 0.2258$. 
Thank you for your attention…

and have a good observing run!