Optical Spectroscopy: In Practice

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Gratings

- Ruled gratings with spacing $\sigma$
- Gratings work interferometrically (not refractively)
- At a given angle, certain $\lambda$ add, certain destruct
- Grating equation: $\sigma(\sin \alpha + \sin \beta) = m\lambda$
- $k$ = order number

Figure 2 - Spectrograph Configuration
What does all this get us?

- Continuum shape distinguishes type of emission
- Also blackbody temp, etc.
- Lines: atomic/molecular composition; physical conditions
Spectral observing modes

- "Long-slit" spectroscopy
- "Echelle" spectroscopy (slang)
- Integral-field spectroscopy
Long-slit spectra

- Slit spatial dimension typically size of detector
- Stars only part of slit
- Extended objects spatially resolved, still underfill slit
- Allows measurement of sky background
Example long-slit spectrum
Example long-slit spectrum
Cross-dispersed Spectra

- "Spatial" direction also has spectral (order) info
- "Slit" may be simple hole, or slit much shorter than detector
- May need to move off-target to get sky background
Things to correct

- CCD detector effects
  - electronic offsets
  - QE/gain variation
  - dark current
- Sky background
  - continuum
  - lines
- Sky absorption
  - wavelength dependent!
How to correct them:

- Electronic offset/dark current: dark frames
  - Exposures with no light entering slit
  - Exposure times match target (why?)

- Gain variations: dome flats (why not sky?)

- Sky background
  - long slit: subtract off-target rows
  - echelle: subtract off-target exposure

- Sky absorption
  - due to molecular bands
  - divide by "spectral flatfield" (featureless star)
Spectral Observing

- Target images
- "Dark" images
- Dome flat images
- Sky images (if necessary)
- Spectral flat images
- What else are we missing?
Lamp Spectra

- Lamp = fluorescent bulb
- Typically helium, neon, argon, xenon, etc.
- Each element has spectral lines with precisely measured/calculated wavelengths
- Lamp or combination of lamps $\Rightarrow$ lines of known wavelength spread over array
- This then provides a calibration of the wavelength versus pixel number for the spectrum
Example lamp spectrum

Neon Lamp
Spectral Wavelength Calibration

(Notes swiped from John C. Wilson)
Wavelength Calibration

- How do we convert from pixel position \((x,y)\) on detector to \(\lambda\)?

  Use a calibration source with known spectral lines

  Empirically derive a ‘solution’ \((f(x,y) = \lambda)\) using mathematical fitting routines
Wavelength Calibration

Why isn’t the wavelength proportional to pixel position, I.e. linear?

Optics of Prism & Gratings, our primary dispersion elements have non-linear angular dispersions

- $A \propto \frac{dn}{d\lambda}$ (prism)
- $A \propto \frac{m}{\cos\beta}$ (grating)
## Wavelength Calibration

<table>
<thead>
<tr>
<th>Spectral Source</th>
<th>λ Regime</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc Lamp (e.g. Argon, Neon, etc.)</td>
<td>UV-NIR</td>
<td>all, but watch for blended lines</td>
</tr>
<tr>
<td>OH lines</td>
<td>NIR</td>
<td>R &gt; 600 to resolve blends</td>
</tr>
<tr>
<td>Planetary Nebulae (H/He emission lines)</td>
<td>VIS-MIR</td>
<td>low (insufficient lines for high res)</td>
</tr>
</tbody>
</table>
Wavelength Calibration

- How often must one observe a calibration source?
  
  As often as required to be certain the ‘solution’ has not changed.
  
  Depends on instrument mechanics, resolution, and observation program

- Why would the solution change?
  
  Movement of the orders on the detector
    - Mechanical Flexure of Instrument Optics
    - Changing thermal conditions inside instrument
Wavelength Calibration

- Example: CorMass NIR echelleogram $\lambda$ calibration using NGC 7027 Planetary Nebulae lines
  
  low resolution, low $\lambda$

- Solution in two parts *
  
  - $f(\text{order}, \text{pix col}) = \lambda$
  - $f(\text{order}, \text{pix}) \to f(x,y)$

* we assume slit image aligned with column. If not gets more complicated.
Wavelength Calibration

- To solve \( f(order, pix \ col) = \lambda \) need:
  - line list
  - line atlas to identify lines in spectra
  - computer program for multi-order fitting

- Game plan
  - get discrete data points for fit: specific \((order, col) = \) known line
  - line center solved using spectral line profile fit routine
  - do this for as many lines / orders as possible
  - solve for analytic soln using 2D polynomial (e.g. chebyshev or legendre) fitting routines
Wavelength Calibration

- Evaluate fit by plotting (residuals v. \( \lambda \)) and (residuals v. pix)

  residuals = difference between analytic soln and discrete point

- Improve fit

  more lines / coverage
  higher order fit
Wavelength Calibration

* For \( f(\text{order}, \text{pix}) \rightarrow f(x, y) \):

  A different routine is used to ‘trace’ the order curvature across the array
Spectral Line Profiles

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Line Profiles

- Instrumental and intrinsic
- Instrumental comes from the spectrograph itself
- One way ⇒ illumination from slit (re-imaged on detector w/dispersion)
Intrinsic Line Profiles

- Intrinsic to the emission source (duh!)
- Emission vs. \( \lambda \) not a delta function
- Examples:
  - Doppler broadening; P-Cygni profiles
  - Density/pressure broadening
  - Lifetime broadening
  - Zeeman broadening
  - Gravitational redshift
Doppler Broadening

- $\delta \lambda / \lambda = v/c$
- $I(\nu) \Rightarrow I(\lambda)$
- Stellar rotation broadens line
- Stellar winds produce "P-Cygni" profile
Density/pressure/Zeeman broadening

- Effects that shift quantum energy levels also shift line wavelengths $\Rightarrow$ line profiles
- Extreme density $\Rightarrow$ E-field shifts levels
- Pressure $\Rightarrow$ distort orbital shape and energy levels
- Zeeman $\Rightarrow$ magnetic field shifts levels

LSD profiles of profiles HR 1099, 1995 Dec. 08
Lifetime Broadening

- Quantum uncertainty effect
- \( \Delta E \leftrightarrow dt \) (dt = lifetime in energy state)
- \( \delta \lambda = \frac{hc}{\Delta E} \)
- Lorentzian profile
Gravitational Redshift

- Extreme gravity redshifts light
- Fe-line from near black hole in ctr of a galaxy
- Includes Doppler blue/redshift and grav. redshift
Radial Velocities
Redshifts

- $\frac{\delta \lambda}{\lambda} = \frac{v}{c}$
- Universe expanding; $v = H_0 \ d$
- Measure galaxies recessional velocity plus 2-D sky position $\Rightarrow$ get 3-D position in the Universe
Correlation Functions

- Two functions
- Similarity as a function of "shift"
- Write equation
Template Galaxies
Results: Large-scale structure

ClA2 First 8 Slices
8.5 ≤ δ < 42.5
< m_g < 15.5