Topics in Observational Astrophysics

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Lecture 5

- Long slit spectrographs
- Spectrographs using reflection gratings
- Imaging spectrographs
- High resolution spectrographs (echelle spectrographs)
- Multi-object spectroscopy
- Integral field spectroscopy
- Imaging Fabry-Perot interferometer
- Fourier transform spectrometers

A long slit spectrograph

This layout is how it would look for a VPHG

2 different 3D views

No anamorphism in this case
Reflection Grating Spectrographs

- A common way to provide the correct image scale at the detector is to give the collimator and the camera different focal lengths.
- The collimator and camera are therefore separate and distinct optical systems and they cannot occupy the same space.
- There has to be some significant angle in between their optical axes so they can both “look at” the reflection grating.
- To meet the blaze condition the grating blaze axis must bisect the angle between the collimator axis and the camera axis.
- There are two possible ways to do this: “normal to camera (Ebert)” and “normal to collimator”.
- The Ebert configuration is preferred because it gives greater wavelength coverage for a given detector width.
"Anamorphism" occurs because magnification in spatial and wavelength directions are not the same.

**Grisms: blaze condition**

The blaze condition for a grism is that the refraction at the facets has the same output angle as the diffraction.

In this example the blaze wavelength is undeviated and the prism angle is equal to the blaze angle.

This is a common configuration in astronomy.
Basic layout of a grism imager/spectrograph

The imaging mode is converted to the spectrograph mode by putting in a slit (or a slit mask) and a grism. There is no anamorphism.

A volume phase holographic grating (VPHG)

The grating layer is sandwiched between two glass plates and is made of gelatin. In this layer the refractive index varies sinusoidally (from top to bottom in this diagram).

The grooves are orthogonal to the plane of this diagram.

Maximum efficiency is when the grating meets the Bragg condition.

\[ \alpha = \beta \]

\[ \gamma = 90^\circ \]

“Blaze” configuration for a VPHG
High resolution echelle Spectrographs

• We can use two dispersers in the collimated beam instead of just one.
• The main disperser (the echelle grating) has its grooves parallel to the slit as before and it uses very high spectral orders (m \(\sim\) 100).
• The second disperser disperses the light at right-angles to the main disperser. This is a prismatic disperser or a reflection grating or a VPHG.
• This gives a 2D data format (an echellogram) on the detector which is useful because this matches available detectors and camera optics.
• The echellogram combines very large wavelength coverage with extremely high spectral resolution.

The configuration for an echelle grating

• Both i and \(\theta\) are large and \(i \approx \theta\) (Littrow or near-Littrow configuration). \(\Rightarrow\) a small camera-collimator angle.
• Échelle in French means stairs or ladder.
• The grooves are relatively large because the spectral order is high.
Spectral order $m$

Wavelength $\lambda$ Angstroms

Length of each order indicates the free spectral range (see example sheet).

Diagram shows how light falls on the detector for a point source at the spectrograph input.

Solar spectrum taken with the HIRES echelle spectrograph on the Keck telescope
The Keck HIRES echelle spectrograph

The collimated beam is 1 ft in diameter and the grating is 4 ft long.

Multi-Object Spectroscopy

• By using many slits, instead of just one slit, it is possible to measure the spectrum of many stars or galaxies at the same time. Need to make a new slit mask for each field of targets.

• An alternative method is to use optical fibres to “pipe” the light from the telescope focal plane to the spectrograph. Need a device to position the fibres.
Multi-object spectroscopic raw data using multi-slits

Instead of a long thin hole (the slit) we have a set of optical fibres.
Multi-object spectroscopic raw data using optical fibres

SDSS (Sloan Digital Sky Survey)

Fibres are manually plugged in to pre-drilled “plug-plates”
Picture shows a plate ready to be installed on the 2.5m telescope (seen in background).
2dF Multi-Object Spectrometer.
(Anglo-Australian Telescope.)
Uses a pick-n-place robotic fibre positioner.

2dF= 2 degree field
400 fibres
400 spectra

The 2dF (2 degree Field) multi-object spectrograph

Fibres are positioned in the focal plane by a pick and place robot.

There are two field-plates: one collects light from the telescope while the other (the one you can see in the picture) is being set up by the robot for the next observation.

Parry, I.R., et al. High Precision Fibre Positioning for the Prime Foci of 4-metre class Telescopes, in Fiber Optics in Astronomy II. P.M. Gray, Editor 1993, p. 34.
Integral Field Spectrographs

- An integral field spectrograph (IFS) is one which measures a spectrum for each and every pixel in the image plane. In other words it creates a data cube with each value in the cube being the light intensity as a function of its wavelength and its position in the image, I(x,y,λ).
- There are several ways to implement such a system:
  1. Image slicer (mirrors)
  2. Lens array (creates an array of micro pupil images)
  3. Lens array + fibres
  4. Fabry-Perot interferometer (tuneable filter)
  5. Imaging Fourier Transform Spectrometer

Image slicing IFS

- The output of the slicer is the input to a dispersing spectrograph.
- The 2-d image is sliced into a “1-d” image (i.e. a very narrow image).
- The region bordered in red at the telescope (slice 4) is the same as the region bordered in red at the spectrograph input.
- In the illustration the 4 slices which are in a horizontal line at the input to the slicer are stacked into a vertical column at the output of the slicer.
JWST/NIRSpec image slicing IFS

Closs et al, 2008

Optical layout schematic

Lens array IFS

Telescope focus
- The lens array is in the image plane.
- The output of the lens array is the input to a dispersing spectrograph.
- Each lens creates a micro-pupil image of the telescope pupil which acts as the spectrograph “slit”.
- The dispersion direction is angled so that the spectra do not overlap on the detector and most of the detector pixels are used.
- Number of spectral resolution elements (SREs) is limited.
- Good when the x, y dimensions of the cube are more important than the λ dimension.
P1640 data for a monochromatic light source. This is essentially a monochromatic image of the array of micro pupils created by the lens array. Notice how the micro pupils are much smaller than the distance between them (which is the size of the individual micro lenses = 75μm square). There are 270x270 square lenses in the micro lens array.

Credit: Stephanie Hunt
Lens array + fibres (IFS)

- Again the lens array is in the image plane.
- Each lens creates a micro-pupil image which is fed into an optical fibre.
- The ends of the optical fibres are arranged in a long slit as for multi-object spectroscopy.
- The use of optical fibres prevents the spectra from overlapping and allowing far more spectral resolution elements (SREs) to be captured for one spatial point than with a lens array on its own.
- Good when a big \( \lambda \) dimension of the cube is more important than the \( x, y \) dimensions.

Fore-optics are needed to match the image scale on the sky to the lens array

SPIRAL was an IFS built for the AAT
Changing the image scale only involves changing the **magnifying lens and two distances**  
(from the telescope focal plane to the lens and from the lens to the pupil image)
CIRPASS Gemini-S, 8m
The back of the macro-lens array with the fibres glued on. Every fibre was placed one at a time with an accuracy of <2μm.

Finished integral field unit with field lens.

1000nm-1800nm, Used on Gemini South.
CIRPASS IFU
FOV and image scales on Gemini-S

499 elements in IFU with 50μm fibres. 1000-1800nm operational wavelength range with spectral resolution $R$ of $\sim$5000.

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

<table>
<thead>
<tr>
<th>Option</th>
<th>Arcsec/lens</th>
<th>Field of view</th>
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<tr>
<td>1</td>
<td>0.36</td>
<td>13.0x4.7</td>
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<tr>
<td>2</td>
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<td>9.3x3.5</td>
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<tr>
<td>3</td>
<td>0.12</td>
<td>4.7x1.7</td>
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Fabry-Perot interferometer

- The FPE acts as a tuneable filter.
- It consists of two very flat glass plates separated by a very small distance. Interference within the plate cavity only allows certain wavelengths to be transmitted.
- The image captured is essentially monochromatic (although the wavelength varies slightly with distance from the centre of the field).
- To make a data cube the FPE has to be scanned through a range of wavelengths by changing the separation of the two glass plates.
**A Fabry-Perot Etalon**

An additional filter is used to select only one transmission peak.

Sharpness of profile (finesse) depends on reflectivity.

Finesse = FWHM/FSR

**Imaging Fourier Transform Spectrograph (IFTS)**

A sketch of a 2-port imaging FTS (IFTS). Only collects half the light.

Imaging FTS

- By scanning the moving mirror, interferograms are measured for each and every point in the image plane, i.e. capture a sequence of measurements: light intensity as a function of the scanning mirror position.
- If the position in the focal plane is given by (x,y) and z represents the mirror position then the data is a data cube, I(x,y,z).
- Spectra for every point (a fixed x and y) are then obtained by taking the Fourier transform of each interferogram → I(x,y,λ).
- Can give extremely high spectral resolution.
- Can be arranged to have two detectors so that the missing half of the light is also captured.
- Signal-to-noise ratio (SNR) for a single SRE depends on the noise from all wavelengths simultaneously. Therefore, the exposure time to get to a given SNR for a single image pixel is longer than for a dispersing spectrograph (this is a big drawback for astronomy).
- However, it captures more spatial pixels in one go.
- Can be useful for applications which need many spatial pixels but only a few wavelength channels and high spectral resolution.