UV/Optical/IR Astronomy Part 2: Spectroscopy

Introduction

We now turn to spectroscopy. Much of what you need to know about this is the same as for imaging – I'll concentrate on the differences.

Slicing the Data

Each photon that hits the telescope can be described by several parameters:

- The Right Ascension of where it came from
- The Declination of where it came from
- Its wavelength
- Its time of arrival
- Its polarization amplitude
- Its polarization angle

Unfortunately, CCDs and most IR detectors only record an x and y position. When imaging, this means they just record where the light came from, (RA and Dec) but not its wavelength, polarization or time of arrival.

Ignoring arrival time and polarization, we are still left with a problem – we want to record 3D data (position and wavelength) but only have 2D detectors.

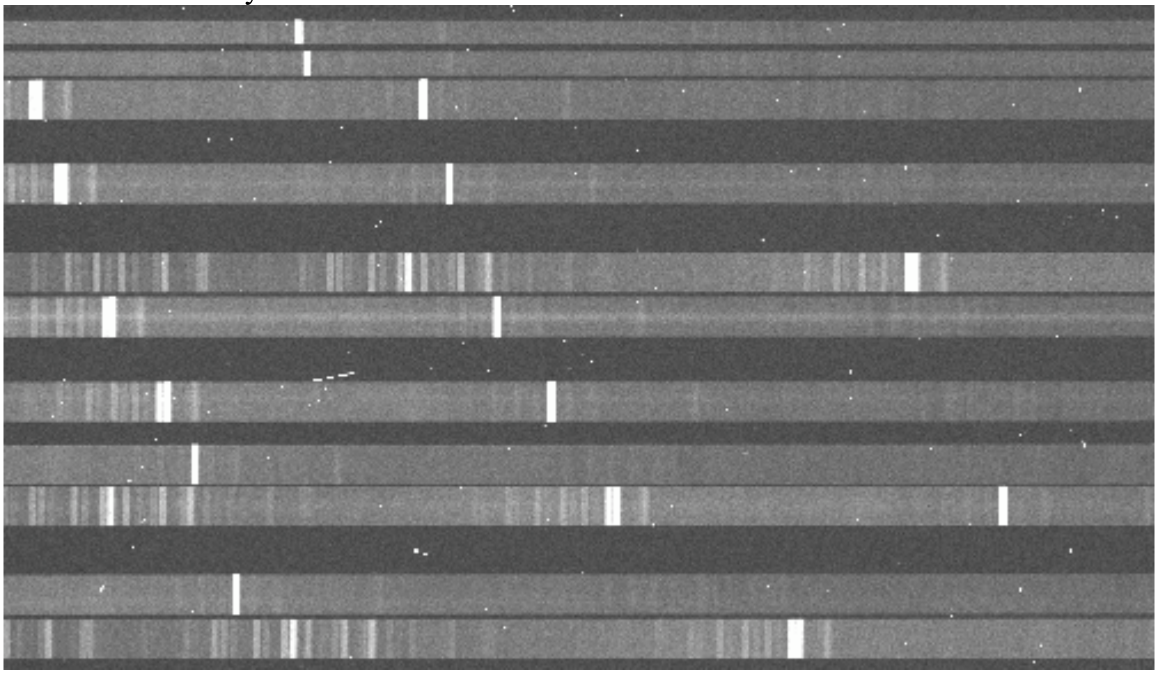
There are several approaches to slicing up this 3D data into something that will fit on a 2D detector:

- **Long-slit spectroscopy.** You put a mirror with a slit in it at the focal plane of the telescope. Most of the light bounces off the mirror (often to an imaging acquisition camera, used to check what target you are observing). But a small fraction of the light falls down the slit. This light is then dispersed by a prism or grating, and lands on the detector. One axis on the detector thus corresponds to position along the slit, while the other corresponds to wavelength.
- **Narrow-band imaging.** Basically straight-forward imaging, but you use a very narrow-band filter, or a Fabry-Perot Etalon (basically a tunable filter) to pick out only a tiny range of wavelengths. So you get an image of a wide region of sky at a particular wavelength, but no information at other wavelengths. By taking repeat observations with different filters, you can build up a crude spectrum of everything in your image.
- **Fibre Spectrographs.** Often, you want to obtain spectra of lots of small objects spread over a wide area. Rather than do them one at a time, you can use the light-bending properties of fibre-optics. You work out where the image of each target is going to fall on the telescope focal plane. You put the end of a fibre there – it intercepts the light and sweeps it away to a spectrograph. You may be able to fit several hundred 1D spectra of different objects into a single detector.
- **Multi-slit spectrographs.** Rather like a long-slit spectrograph, but instead of one long slit in the focal plane, you cut a special mask containing lots of short slits which will fall on top of lots of targets. This way you effectively get lots of slit

spectra of different targets at once. Typically more efficient than fibre spectrographs, but only works with smaller fields of view.

- **Integral Field Units (IFUs).** Using a bundle of fibres or an array of tiny mirrors, the light landing in a small region is sliced up into lots of long-slit or fibre spectra, which fall on your detector. It gives you a full spectrum of every point in a small region.

Here is an example – part of a spectrum taken with GMOS on Gemini. This is a multi-slit spectrograph – each of the grey bars corresponds to one little slit in the mask. Wavelength increases to the left – position along each slit increases upwards. The white bars are night sky emission lines – as the sky glows at every position on every slit, they cover the whole vertical extent of each slit. In most of these slits, the target galaxy is too faint to easily see – but you can pick them out in a few cases as horizontal fuzzy bands.



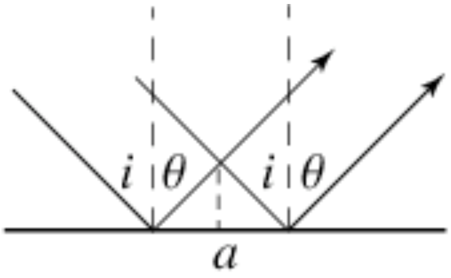
Dispersers.

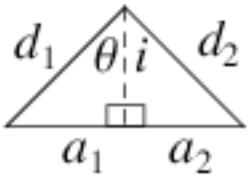
A spectrograph needs something to separate out the different wavelengths and send them to different parts of your detector.

The simplest and most efficient method is a **prism**. Due to the wavelength dependence of the refractive index of most glasses, this separates out different wavelengths. If the prism surfaces are appropriately coated, this can be extremely efficient, losing very little light. But it tends to give a pretty low resolution. It is often used for very low dispersion spectroscopy, because of its very high throughput.

The most common method is to use a **diffraction grating.** In its simplest form, this is just a mirror or a piece of glass with lots of lines marked on it. Light bouncing off it will constructively interfere only at certain precise angles, where the light bouncing off each bit adds up in phase.

Consider light bouncing off a mirror:





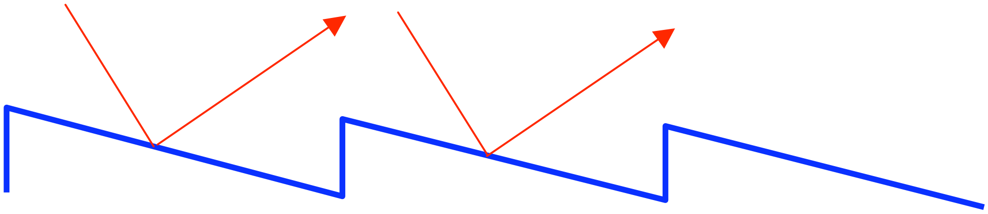
The path length Δ between the two rays can easily be calculated by solving the following four equations in four unknowns: $a_1=d_1\cos(\theta)$, $a_2=d_2\cos(i)$, $a = a_1+ a_2$ and $d_1^2-a_1^2= d_2^2-a_2^2$. Solving, we get that:

$$\Delta \equiv d_2 - d_1 = a\left(\sin(i) - \sin(\theta)\right)$$

To get constructive interference, we require $\Delta=n\lambda$, where λ is the wavelength of light and n is an integer. This is the **grating equation**.

For a simple mirror, of course, the obvious solution is $i=\theta$, n=0: the "zeroth order". This is just straight reflection and is not very useful. We really want to get as much of the power as possible into another order – say n=1.

To do this, most gratings use "blaize" – their surfaces are cut into a zig-zag pattern, so that as much as possible of the light ends up in the chosen spectral order.

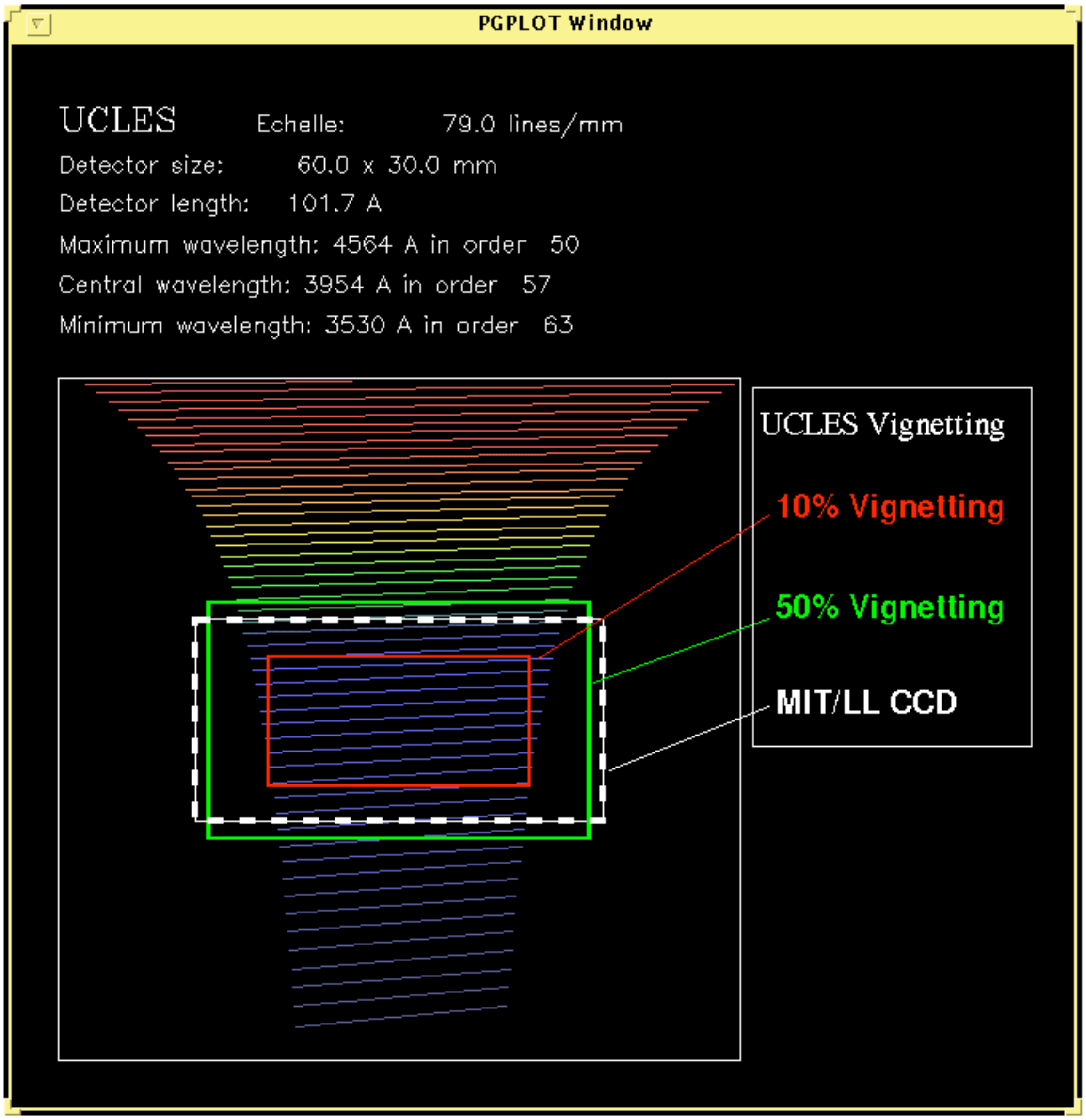


These gratings are cut using a diamond tool that repeatedly scrapes lines in the surface of the substrate material.

Most low/moderate dispersion spectrographs (such as the double beam spectrograph on the 2.3m) use blaized gratings such as these, and are typically run in first order. But beware – the other orders are still present – you will often find the blue second order superimposed on the red end of your first order spectrum, unless you block it with a special filter.

To get higher resolution, you either need to have the "lines" closer together, or to work in a higher spectral order (larger n). Most really high resolution spectrographs use an "echelle" – a blaized grating with really steep notches – the word echelle comes from the French for staircase. They are designed to work in a high order – say n~50. Normally this would mean that all the different spectra orders (n=49, 50, 51…) would overlap, so the output is usually "cross dispersed" – i.e. put through a prism with its dispersion at right-angles to the dispersion of the echelle. This separates out the different orders, and produces a nice rectangular pattern of data, suitable for fitting on a CCD.

Here is an image of where the different parts of the spectrum fall for the UCLES echelle spectrograph on the AAT.



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UCLES      Echelle:         79.0 lines/mm
Detector size:       60.0 x 30.0 mm
Detector length:    101.7 A
Maximum wavelength: 4564 A in order  50
Central wavelength: 3954 A in order  57
Minimum wavelength: 3530 A in order  63
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A common variant on a diffraction grating is a “grism”. This consists of a grating glued to the surface of a prism. Working together, they cause dispersion, but the prism and grating bend light in opposite ways, so that at the central wavelength the light passes straight through. This means that when you remove the grating from the light path, you can get an image. Thus allowing you to do imaging and spectroscopy with the same instrument.

Recently, a new grating technology has come into prominence – Volume Phase Holographic gratings (VPH). These consist of a layer of special material sandwiched between two glass plates. This special material has a periodically changing refractive index (caused by exposure to a laser interference pattern during its manufacture – i.e.a hologram). This introduced the periodic phase shifts needed to cause dispersion, with no need to have an irregular surface. VPH gratings can have much higher efficiency than the old reflection ones – because their surfaces are smooth and they can be tuned to direct almost all of the light into a single order.

Spectral Performance

The performance of a spectrograph is measured by:

- Its spectral resolution R. R measured how far apart two spectral features would have to be for them to be clearly separated out. R=10,000 means that at a wavelength of λ, the spectrograph will separate out features separated in wavelength by at least λ/10,000.
- Wavelength coverage – how wide a wavelength range will you get in one exposure?
- Throughput or efficiency – what fraction of the input photons make it through the spectrograph heading in the right direction, in the correct spectral order?

Signal-to-noise ratio calculations for Spectroscopy.

Calculating the signal-to-noise ratio for a spectroscopic observation is pretty similar to how you do it for an imaging observation. In this section, I'll highlight some of the differences.

- Slit losses/fibre losses. If you are using a slit or fibre to pick out the part of the sky you wish to obtain a spectrum for, some light from your target will be lost because it missed your slit/fibre. How much is missed depends on the size of your slit or fibre, on the seeing, and on the size of your target. If, for example, you have a 0.1" wide slit, but are observing a star in 5" seeing (not unusual at SSO), you will be missing all but a fraction ~0.1/5 of the light. Integral field spectrographs do not have this problem.
- Spectrograph efficiency – you have to factor in light losses in the spectrograph, which are typically much worse than in an imaging camera.
- You now have to calculate the number of object and sky photons you detect *per resolution element.* If, for example, you are working a R~1000 at a wavelength of 500nm, that means that one resolution element is ~0.5nm. So you should work out how many object photons you'll get in this small wavelength interval, and how many sky photons.
- Read noise is often more important. To work it out, you'll need to know over how many pixels on your detector the light from a given resolution element will be spread. The spectrograph manual should tell you how many nm per pixel the spectrograph gives in the dispersion direction. If you know the size of your resolution element, this gives you the number of pixels in the dispersion direction. If it is a slit spectrograph, the manual will also tell you how many arcsec per pixel you get along the slit. This, combined with the seeing, will give you the number of pixels in the spatial direction.
- Signal-to-noise ratios may vary quite strongly as a function of wavelength, as the sky is much brighter at some wavelengths than at others (due to sky lines).