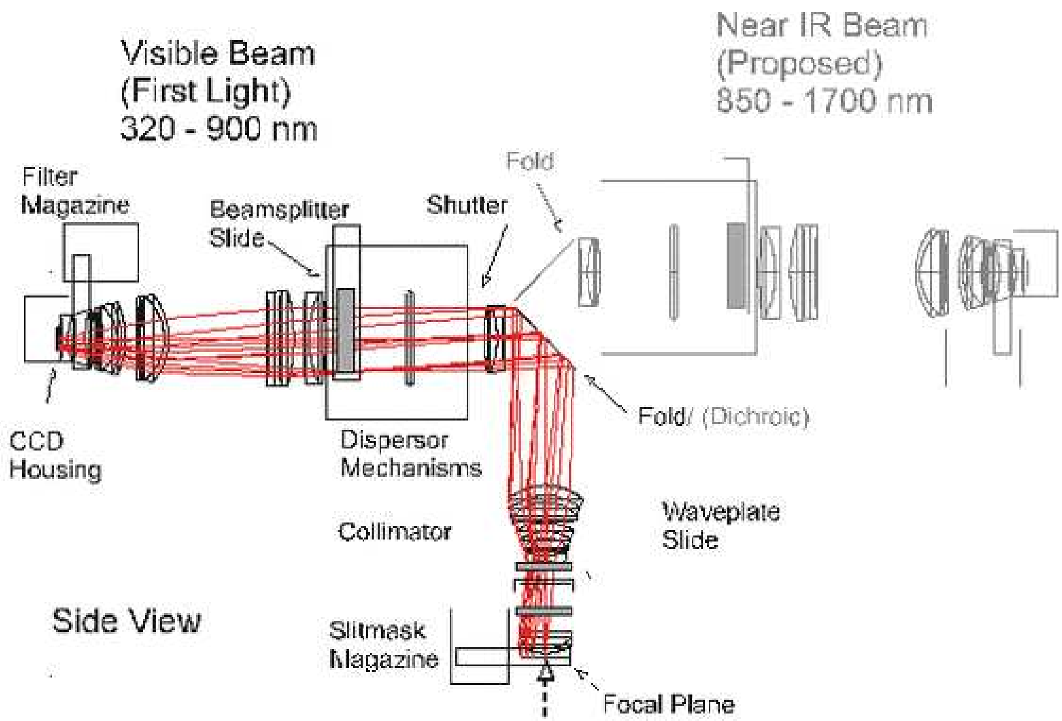
Spectroscopy – II. Spectrographs

Dave Kilkenny



Contents

1 The spectrograph – basic components

As we have already seen, the objective prism is useful for survey work. But there are problems for more detailed spectroscopy:

- the spectra are difficult to calibrate in wavelength – and therefore difficult to use for quantitative measurements..
- spectrum overlap can be a serious problem in crowded fields.
- the dispersion is very poor; resolution is low. Again, it makes it difficult to obtain useful quantitative measurements.

A conventional spectrograph gets around these problems, but in the classical slit spectrograph, typically only one star is observed at a time. (We shall see later how this can be extended substantially).

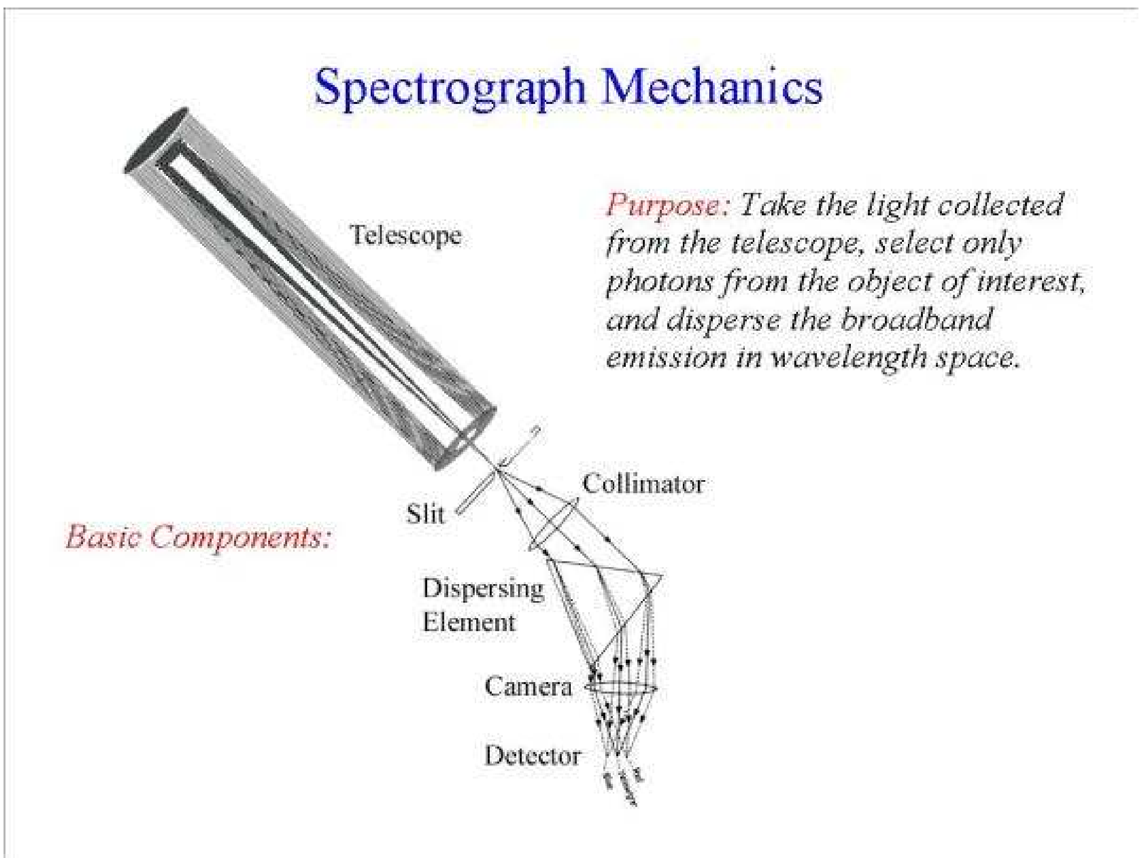


Figure 1: Schematic of a conventional (typically Caasegrain focus) slit spectrograph.

The principal components – slit, collimator, disperser, camera and detector will be briefly discussed.

1.1 The entrance slit

The spectrograph slit enables a particular object (or part of an extended object) to be selected for observation – with the exclusion of other objects. More importantly, because the slit is effectively imaged on to the detector by the spectrograph optics, by keeping the slit narrow enough that the width of the image of the slit on the detector is smaller than or comparable to the detector resolution, we do not lose resolution (= information) at the detector.

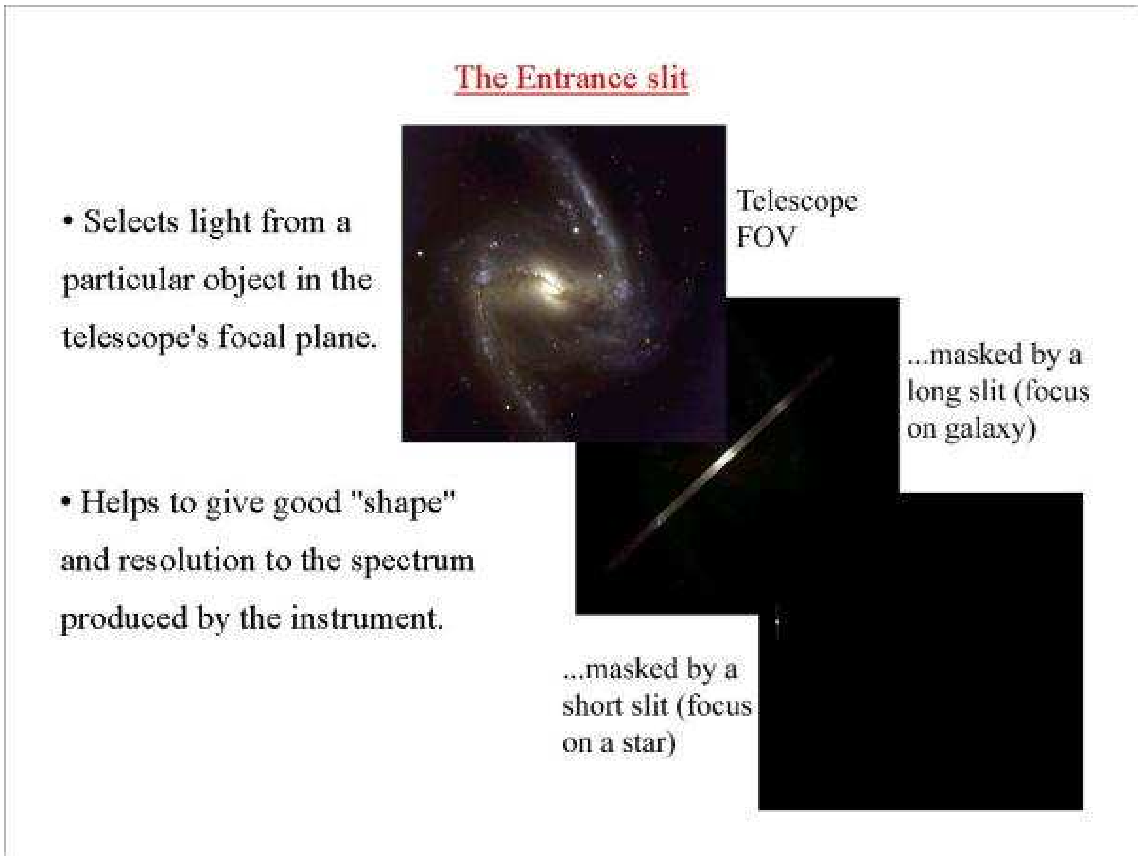


Figure 2:

1.2 The collimator

Recall that the input to double- or multiple-slit experiments requires parallel light. The diffraction grating is effectively a multiple-slit experiment and the **collimating optics** produces a paralle beam of light for the disperser (grating).
As can be seen from the figure, if the collimator optics is not matched to the telescope optics, the collimator can be over-filled – resulting in obvious loss of light – or under-filled – resulting in loss of resolution (remember how the width of the constructive interference bands in the multi-slit experiment reduces as the number of slits increases).

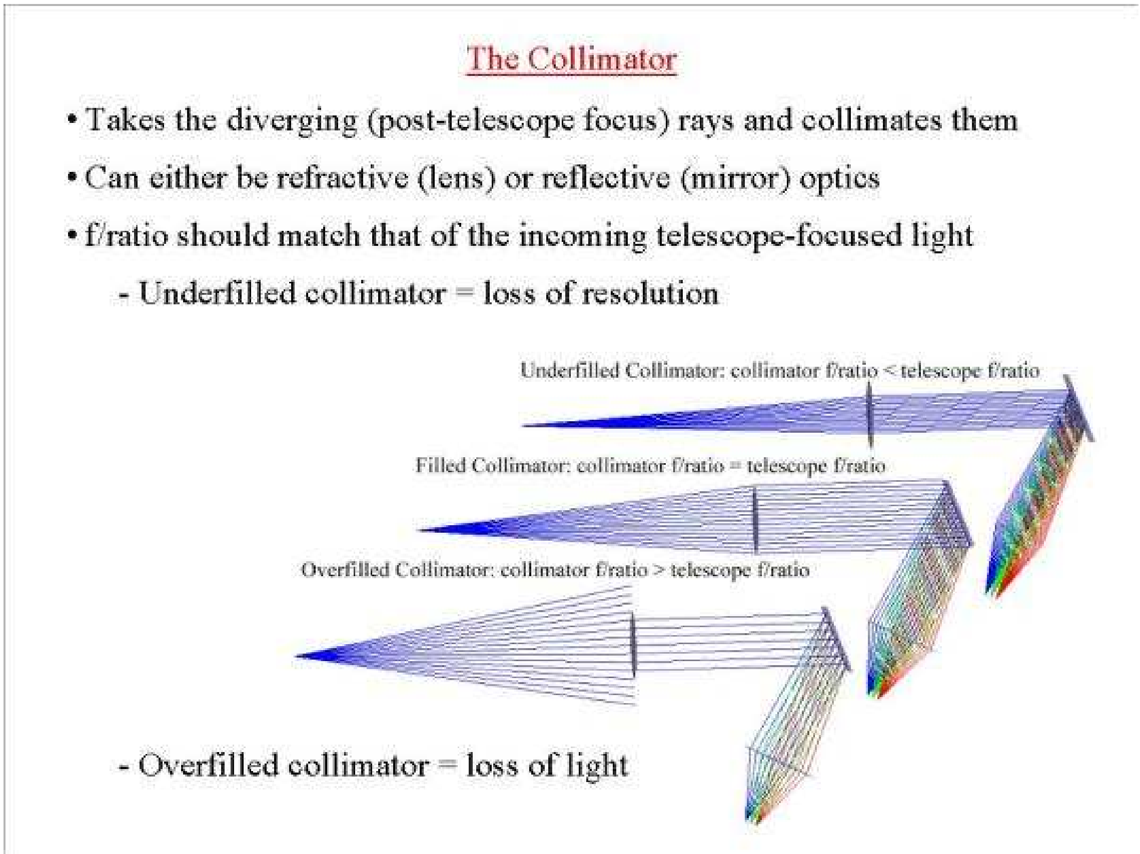


Figure 3:

1.3 The dispersing element

We have looked briefly at prisms – and in rather more detail at diffraction gratings which are perhaps the most common dispersing element used in astronomical spectrographs (including conventional gratings, echelle gratings, VPH gratings and so on) and we will not dwell further on dispersers here. There are other types – Fabry-Pérot etalons, for example – which we will look at later.

1.4 The spectrograph camera

The light emerging from the diffraction grating needs to be brought to a focus on the detector (otherwise the spectrum is "smeared" and resolution is lost.

As noted in the figure, the collimator and camera form an imaging system – which produces an image of the slit on the detector. In the case of monochromatic light, a simple image of the slit would be produced; in the case of dispersed white light, a spectrum is produced. Still, the spectra of most stars contain detailed information (absorption and/or emission lines) which can be quite fine features. In order to preserve resolution, the collimator/camera must image the slit well – and the slit must be narrow enough that the slit (monochromatic) image should be no wider than the resolution of the detector

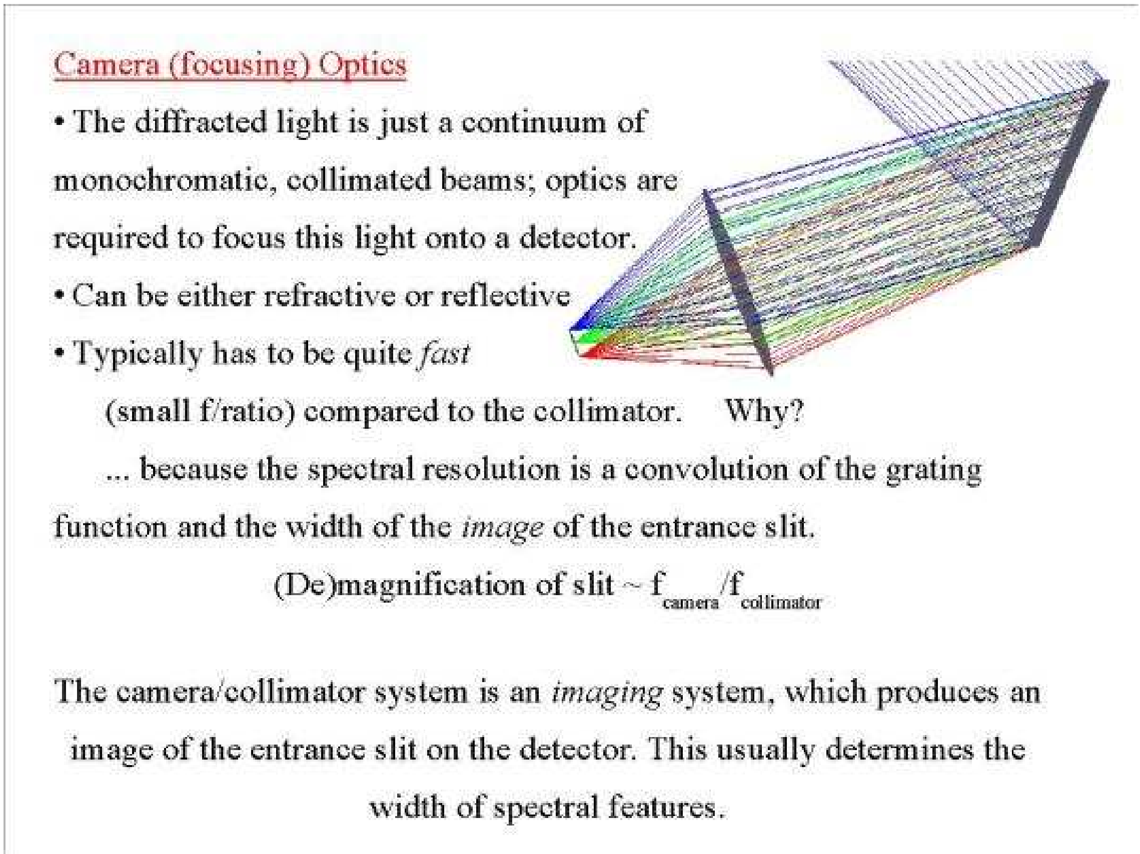


Figure 4:

1.5 The detector

In almost all modern spectrographs the detector is a CCD (or several CCDs). these have been discussed in detail earlier.

The spectrograph elements discussed above are common to many spectrographs. we shall now look in detail at some specific types.

2 Long–slit Spectroscopy

As noted at the start of this lecture, slitless spectrographs (such as objective-prism systems) are difficult to calibrate (e.g. in wavelength). The conventional type of astronomical spectrograph – in use for many decades – is the long-slit spectrograph. The discussion in the previous section was based mainly on the idea of the long-slit spectrograph

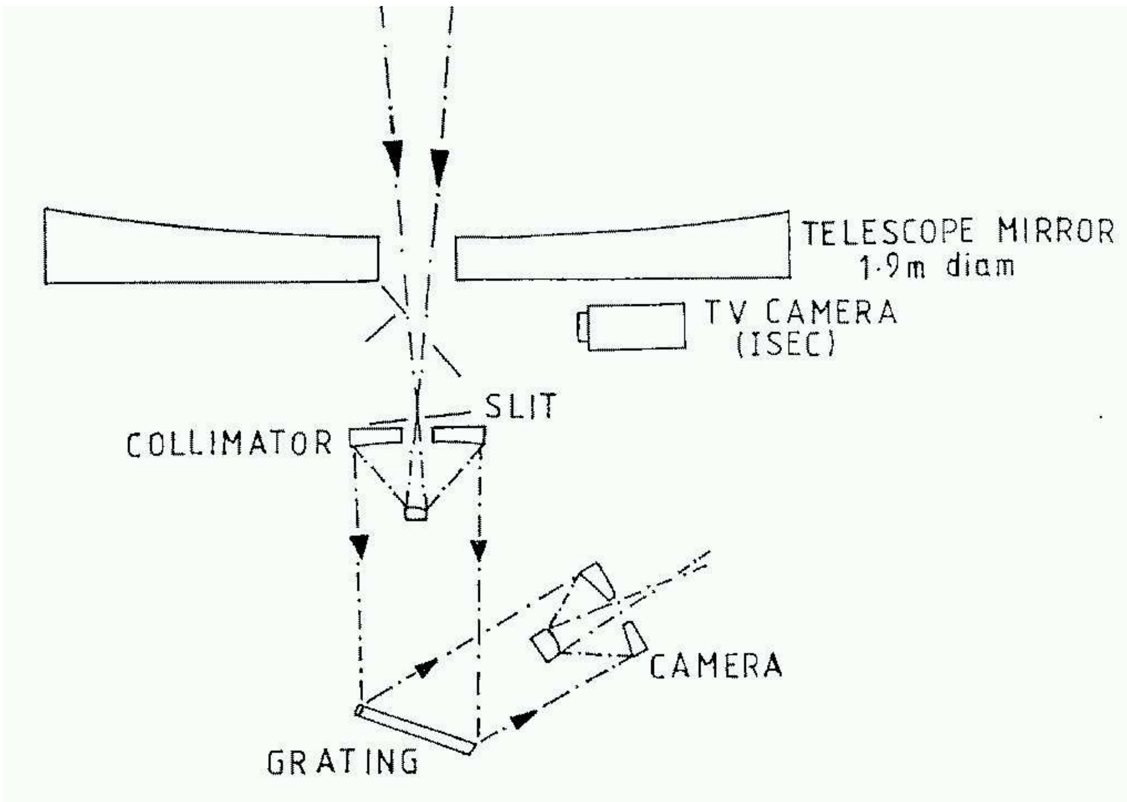


Figure 5: Schematic of the Cassegrain spectrograph used on the SAAO 1.9m

Important elements of the spectrograph are, as before:

- **The slit**. The slit width should be set so that the **projected** slit width seen by the detector should be well sampled by the detector resolution. In addition, for good radial velocity work, the slit needs to be smaller than the seeing disk (so that the slit width is completely filled with starlight) but for faint stars, one might wish to use a wider slit (to get more starlight into the system). For spectrophotometry, one might need to use a very wide slit to make sure of getting all the starlight (losing wavelength resolution to gain photometric accuracy)..
- **The collimator** produces a parallel beam of light for the diffraction grating.
- **The grating** is usually the dispersing element of choice.
- **The camera** focusses the resultant spectrum on to the detector. The camera is often a Schmidt or Maksutov type.
- **The detector** – usually a CCD (or CCDs)

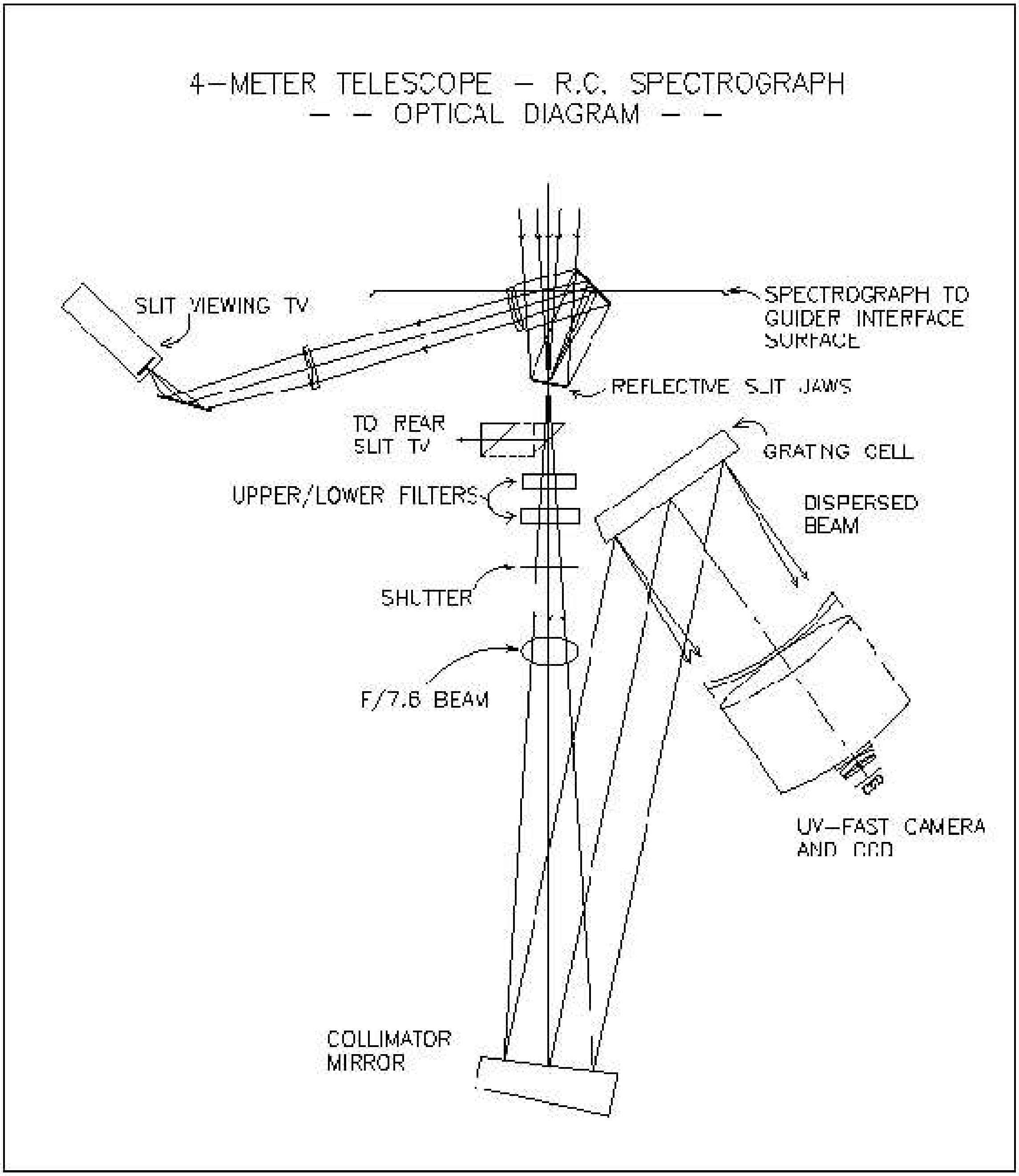


Figure 6: Schematic of the KPNO Cassegrain spectrograph

2.1 Practical notes

- An important result of the grating equation is that if it is satisfied, for example, for a line at 9000Å in the first order, it is also satisfied for a line at 4500Å in the second order, 3000Å in the third order, and so on. (1 x 9000 = 2 x 4500 = 3 x 3000, ...) **In practice, it might therefore be necessary to use an optical filter to prevent order overlap**, essentially to isolate the required order.

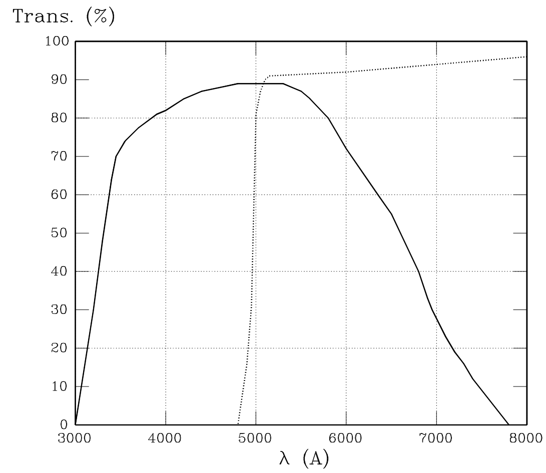


Figure 7: typical "order blocking" filters: solid line BG39; dotted line GG495.

- The long-slit gives some capability for observing extended objects, but only in one dimension, of course. We shall see this later.

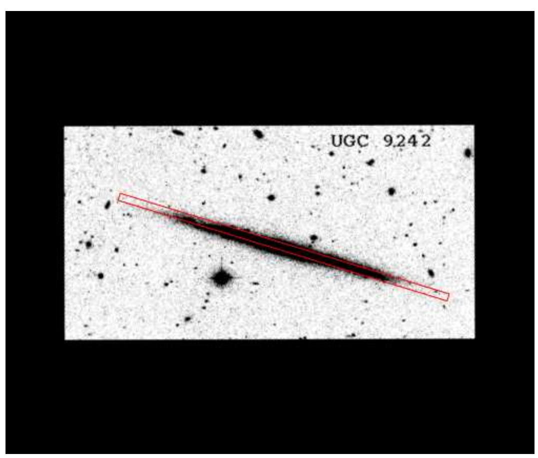


Figure 8: Some spatial resolution (as well as spectral) can be obtained for an extended object such as a galaxy .

- Since we are usually interested in accurately determining the positions of spectral features – initially to identify lines, but also to measure radial velocities – it is necessary to measure calibration "arcs". These are normally produced by arc lamps – gas ionisation in a vacuum tube of some sort – and are often measured before and after each "target" spectrum. They can then be used to calibrate pixels (in the direction of dispersion) in terms of wavelength.

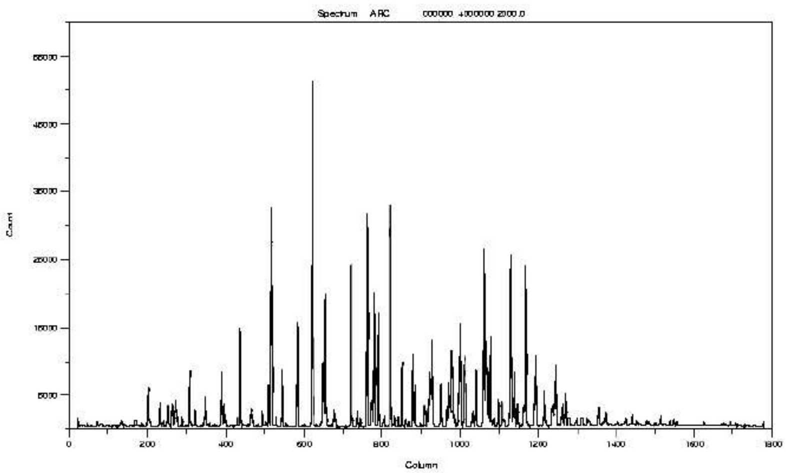


Figure 9:

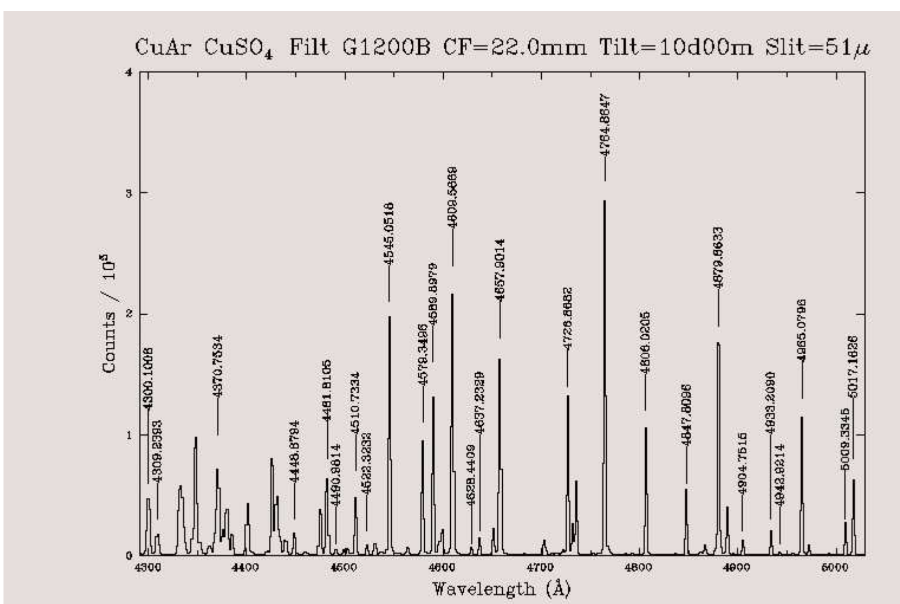


Figure 10: Small range of frequencies from a Copper-Argon arc lamp.

- In addition, if we want to perform **spectrophotometry**, the calibration of the spectrum of the observed object in absolute flux units, we need to observe at least one spectrophotometric standard and to have some calibration of the atmospheric extinction. Essentially, we need to be able to measure the spectrum photometrically – so typically a wide slit would be used, sacrificing resolution.

3 Echelle Spectroscopy

Earlier, we saw that The grating angular dispersion equation

$$\frac{\Delta\beta}{\Delta\lambda} = \frac{m}{d\ cos\ \beta}$$

indicates that the **echelle** grating can achieve high dispersion by operating in high orders, typically $m \sim 100$. Recall that as m becomes large, both β and the dispersion will change little – hence one obtains almost completely overlapping orders of very similar dispersion and the orders need to be separated. To do this, a mild “cross-disperser can be used to separate the orders:

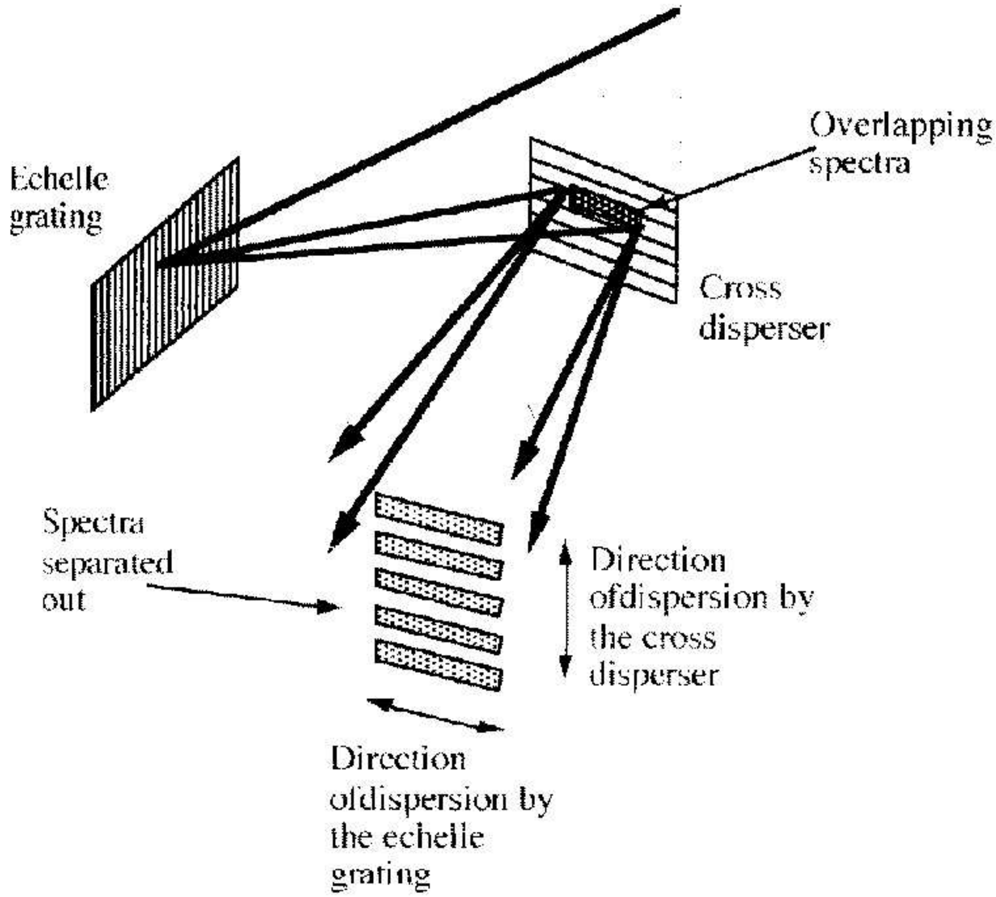


Figure 8.9 Schematic view of an echelle grating and a cross disperser.

Figure 11: Schematic of the use of a “cross-disperser” to separate echelle orders.

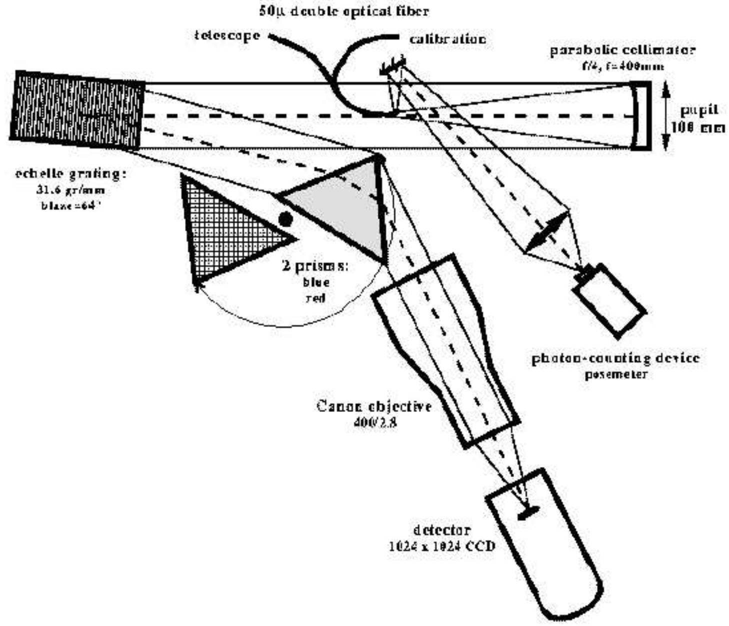


Figure 12: Schematic of the "MUSICOS" spectrograph a copy of which is used on the SAAO 1.9m. The corss-disperser is a prism. Either of two prisms can be used; one optimised for the blue and one for the red.

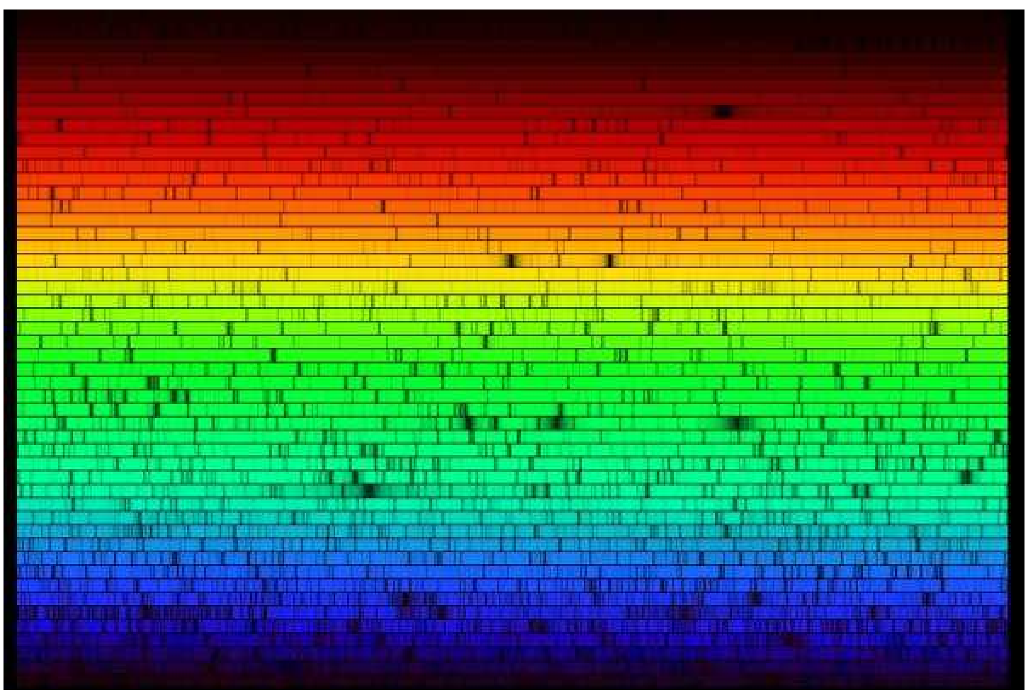


Figure 13: An echelle spectrogram of the Sun. Note the *many* weak lines; strong sodium "D" lines near centre, orange.

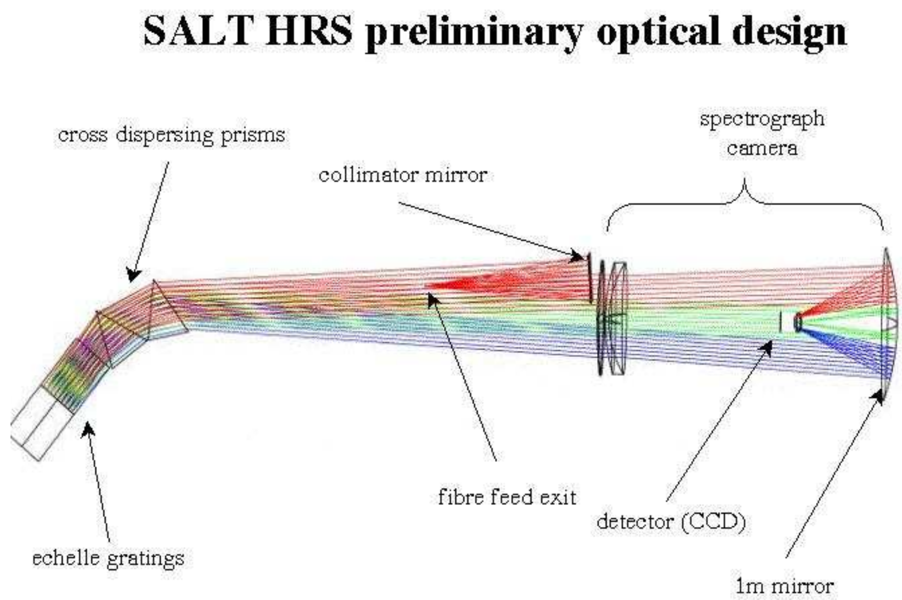


Figure 14: Suggested “double–pass” prism cross–dispersers for the SALT Hi-Res spectrograph.

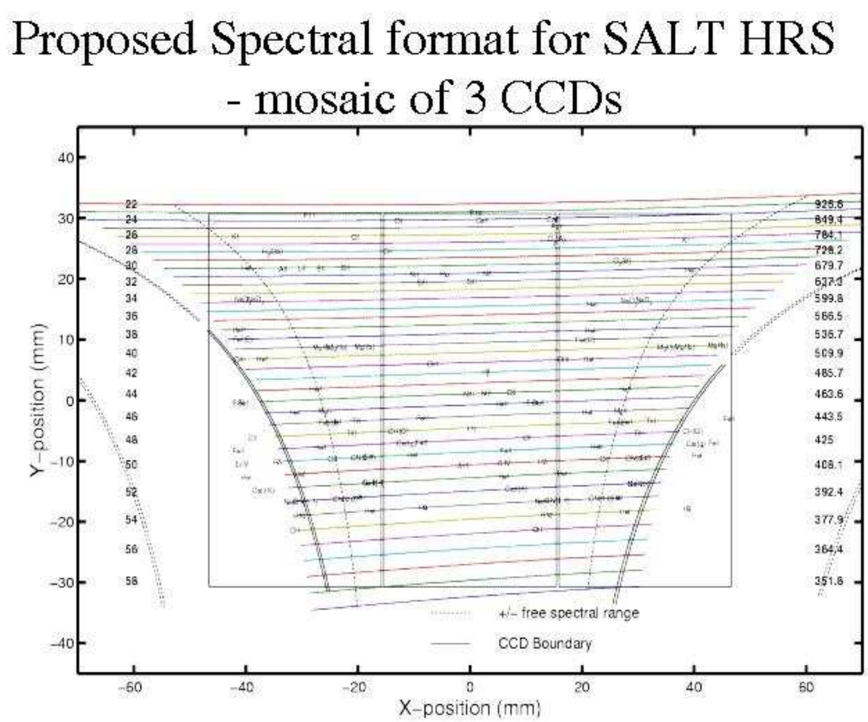


Figure 15: Simulation of the SALT echelle CCDs and order distribution.

Existing and proposed High Resolution Spectrographs on Large Optical Telescopes

Acronym	UVES		HIRES	HDS	HRS	bHROS	SALTHRS
Telescope	VLT		Keck	Subaru	HET	Gemini S	SALT
	Blue	Red					
Wavelength range	300 - 500 nm	420 - 1100 nm	320-1100	320-1100	420-1100nm	400-1000	370-930nm
Resolution-slit product	41,400	38,700	39000	38000	30139	21000	38000
Max. resolution	~80,000	~110, 000	67000	165000	120000	150000	85000
Overall detective quantum efficiency (DQE) (from top of the telescope, wide slit)	12 % at 400 nm	14 % at 600 nm	10 % at 600 nm	13 % at 600 nm	~7 % at 600 nm	12.6 % at 60[illegible] nm	14.7 % at 660nm
Camera	dioptric F/1.8, 70 µm/arcsec	dioptric F/2.5, 97 µm/arcsec	cata-dioptric F/1.0, 762 mm fl	cata-dioptric F/0.96, 770 mm fl	dioptric F/2.8, 120 µm/arcsec	reflecting F/0.96, 770 mm fl	catadioptric f/0.6 1200mm
CCDs and pixelscale	2K x 4K, EEV 15 µm pixels	(EEV + MIT/LL) 2K x 4K, 15 µm	2K x 2K, Site 24µm pixels	mosaic of two EEV 2K x 4K, 13.5 µm pixels	Marconi 2K x 4K, 15 µm pixels	Marconi 2K x 4K, 15 µm pixels	mosaic of 3 E2V 2kx4k 15µm pixels
Echelle	41.59 g/mm, R4 mosaic	31.6 g/mm, R4 mosaic	52.6 g/mm, R2.8 mosaic	31.6 g/mm, R2.9 mosaic	31.6 g/mm, R4 mosaic	100 g/mm, R2	87 g/mm, R2, mosaic
	#1: 1000 g/mm, 360 nm	#3: 600 g/mm, 560 nm	Red: 250 g/mm, 700 nm	Blue: 400 g/mm, 415 nm	#1: 316 g/mm, 610 nm	Prism	Prism
Crossdispersers (g/mm and wavelength of max. efficiency)	#2: 660 g/mm, 460 nm	#4: 312 g/mm, 770 nm	UV: ? g/mm, 470 nm	Red: 250 g/mm, 700 nm	#2: 600 g/mm, 510 nm	Prism	Prism
Maximum wavelength range/frame	126 nm	403 nm	~250 nm	~400 nm	380 nm	~160 <1 FS[illegible]	560nm

Figure 16: Sample of high-resolution spectrographs. Note the resolutions possible and the relatively low efficiencies.

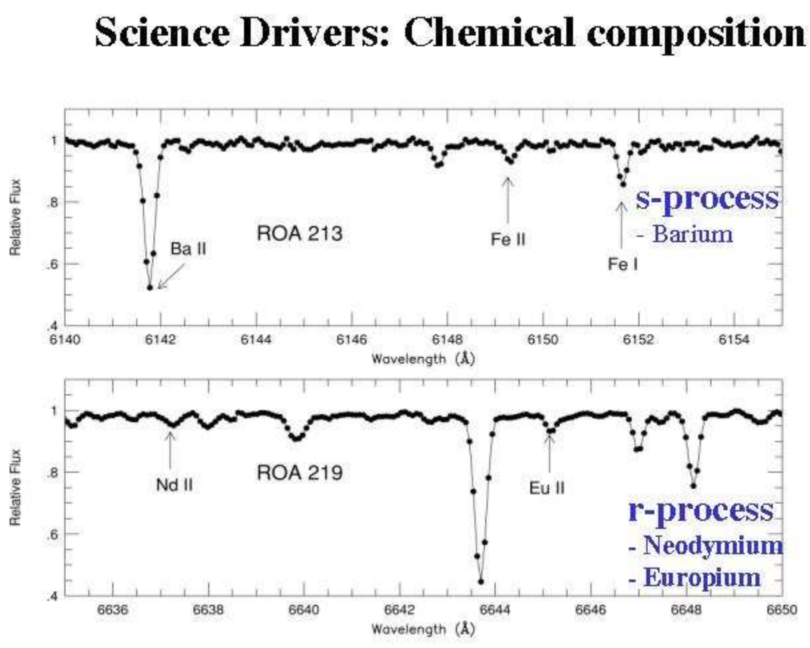


Figure 17: Sample of a single order from an echelle spectrogram.

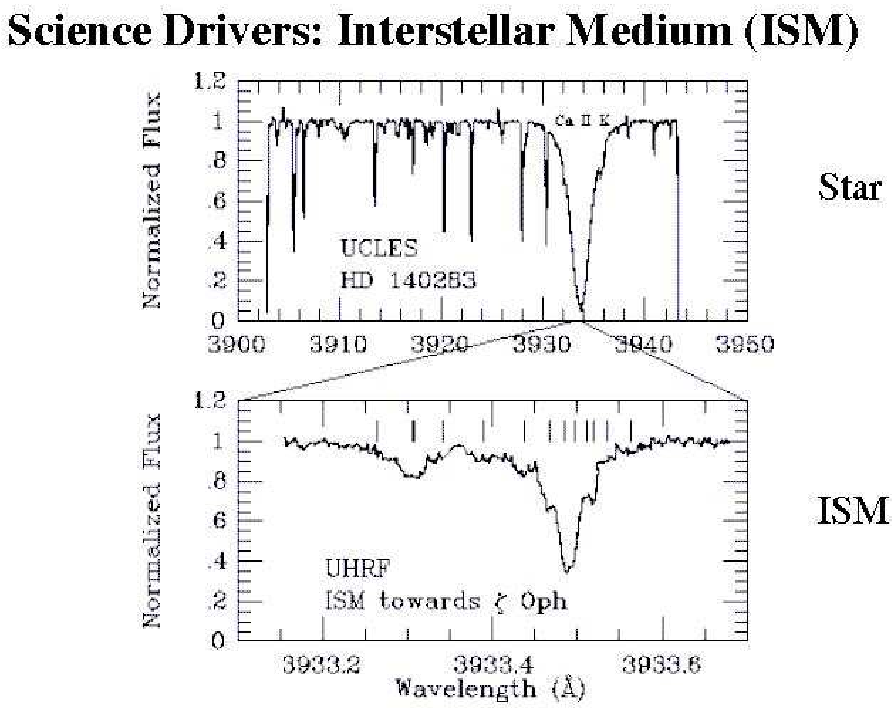


Figure 18: Sample of a single order from an echelle spectrogram.

The advantages of the echelle spectrograph are:

- The very high dispersions attainable (of course) and therefore the very high resolutions (see " science drivers" boxes).
- The large spectral range possible – due to the "compact" nature of the cross-dispersed output.

Disadvantages:

- The more you disperse the light of a star, the less light you get per pixel of the detector. This means that for a given telescope, you would not be able to observe nearly as faint stars.
- Because of the high orders and many orders used, the throughput (efficiency) of echelles is quite low.

  As an example of the above two points, the Cassegrain spectrograph on the SAAO 1.9m can observe to about 17 or 18 mag, at lowest dispersion; the SAAO echelle spectrograph on the same telescope has a practical limit of about 9 – 10 mag.

4 Multi-object Spectroscopy

One clever way of using a conventional spectrograph to observe many objects simultaneously is to have optical fibres placed exactly in the focal plane of the telescope to pick off individual objects, then line up the other ends of the fibres along the spectrograph slit. Examples from the Anglo-Australian Observatory's (AAO) "2 degree field" (2dF) on the 3.6m AAT and the "6 degree field" (6dF) on the AAO Schmidt telescope and the "Hydra" system operated on the US National Optical Astronomy Observatory (NOAO) telescopes.

Figure 19: The 2dF fibre system on the AAT. Each speck on the plate is a small "upward looking" prism in a small magnetic holder feeding an optical fibre. A robotic "gripper" takes each prism and places it on a metal plate. The required accuracy is a few tenths of an arcsecond, so accurate astrometry is needed beforehand.

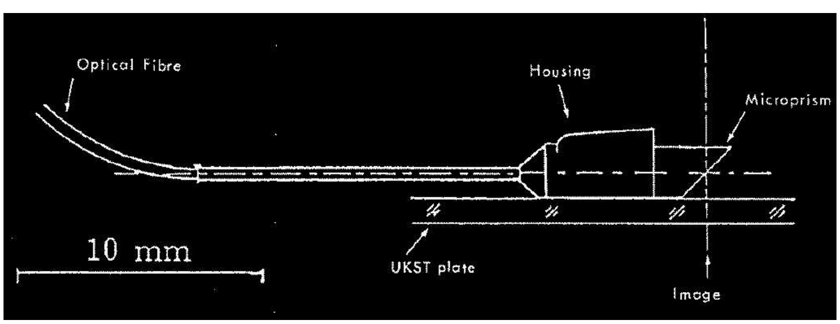


Figure 20: Schematic of a "microprism" assembly from the AAT Schmidt's 6dF.

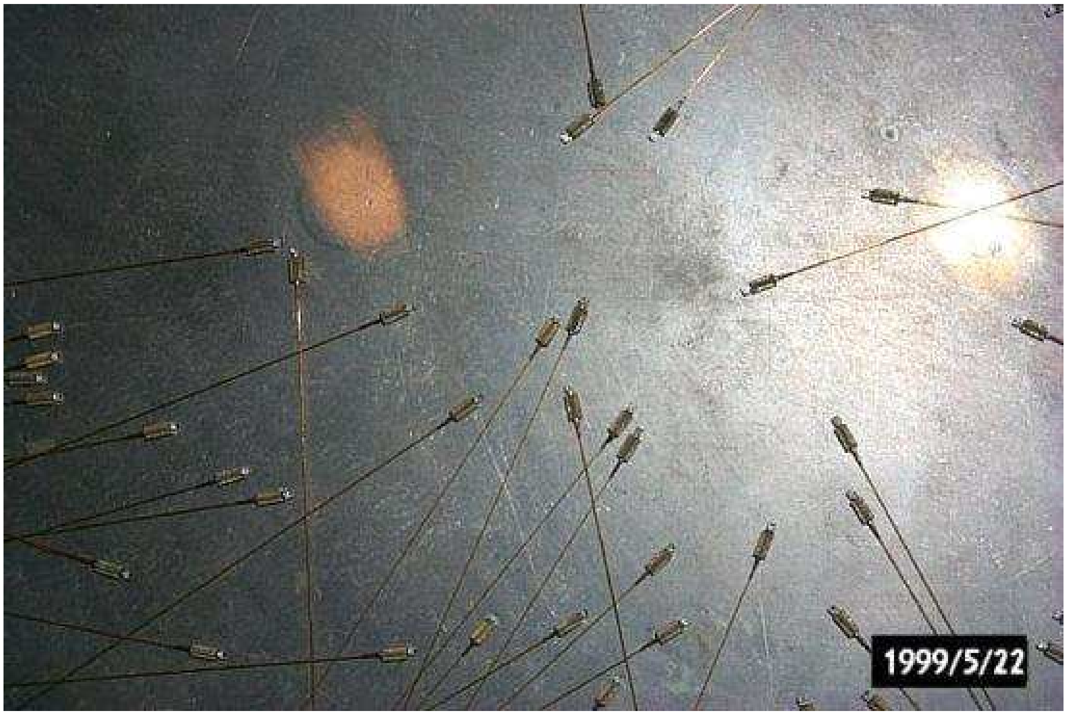


Figure 21: Close up of the 2dF fibre feeds on the metal plate.

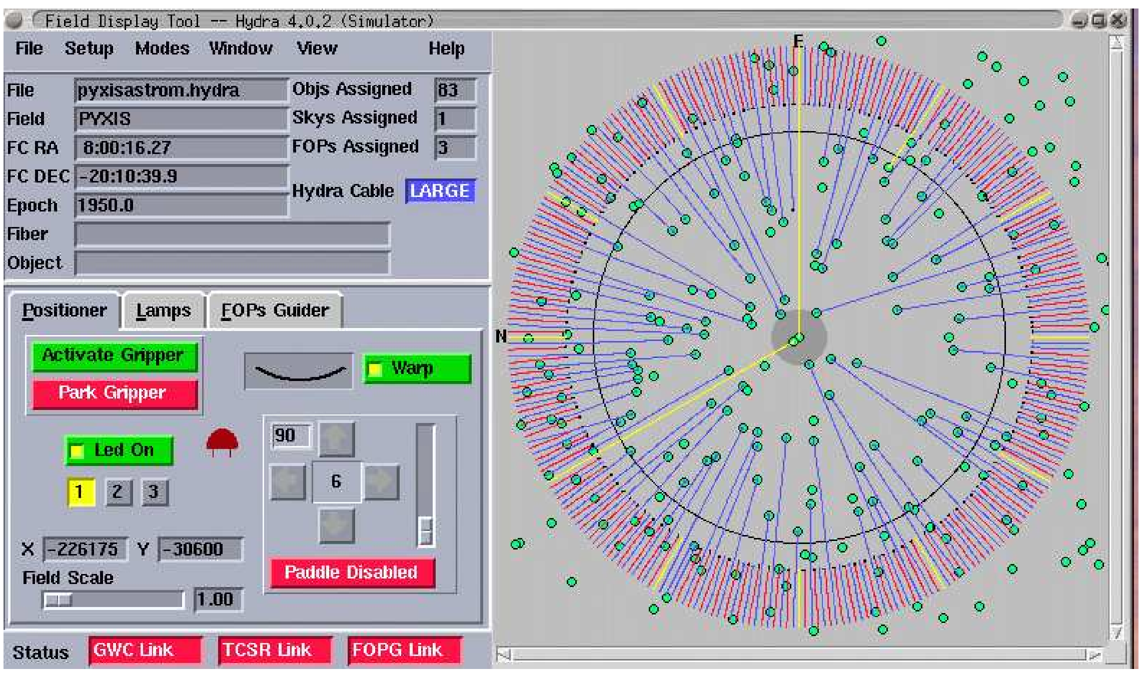


Figure 22: NOAO "Hydra" set-up software interface, set for stars in the Pyxis globular cluster. The yellow–coded fibres pick up "fiducial" bright stars for guiding.

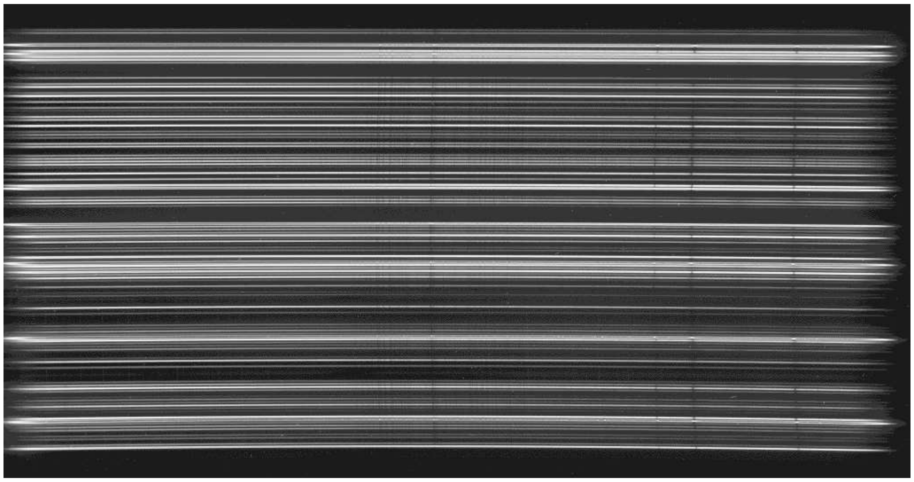


Figure 23: Spectra of $\sim$ 100 stars piped to a single slit.

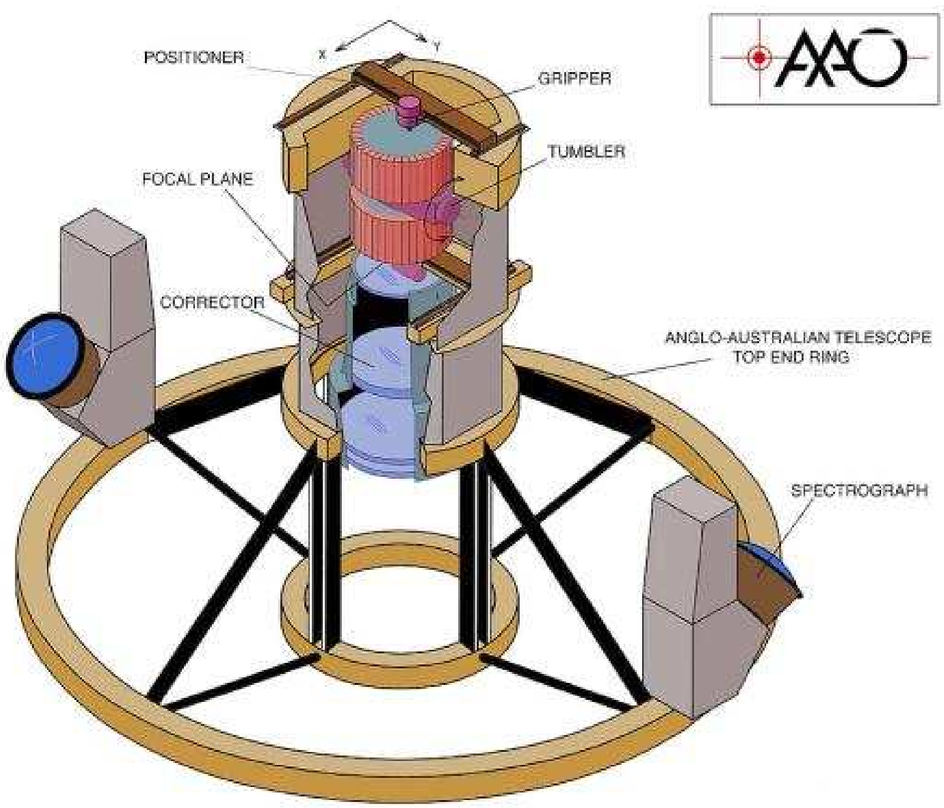


Figure 24: Schematic of the top end of the AAT. This is very smart; since it takes about 30 or 40 minutes to set up each fibre/prism observing field (containing up to 400 fibres) the 2dF has two such systems back-to-back on a "tumbler". Whilst one field is being observed, the other field is re-positioning.

5 Fabry–Pérot Spectroscopy

5.1 Basic idea

A Fabry-Pérot interferometer is a transparent plate with two refelecting surfaces – or two parallel transparent plates with a single reflecting surface each. The former is technically an **etalon**, the latter an interferometer, which has the advantage that changing the plate separation allows one to "tune" the interferometer to a particular wavelength range. (Note: the interferometer is often referred to as an etalon !)

Fabry-Pérot interferometers have many applications where accurate control and measurement of wavelength is vital (telecommunications, spectroscopy, lasers)

If we consider the Fabry-Pérot based on two partially reflecting parallel plates – the interferometer – we have the following schematics:

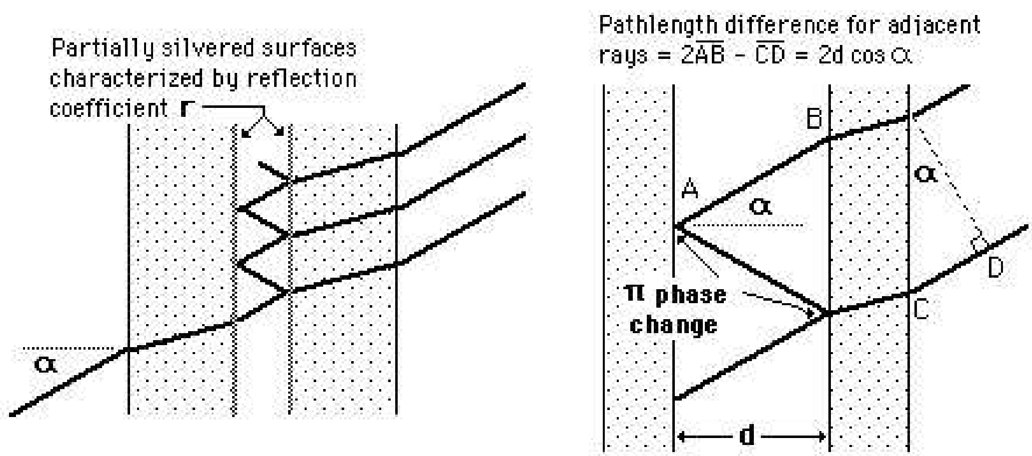


Figure 25: The basis for a Fabry-Pérot interferometer (note: the angle α is exaggerated for clarity).

When collimated light passes through the plates, the path difference is 2 AB - CD (see the above figure) which is:

$$2 \, \frac{d}{cos \; \alpha} \; - \; 2 \; d \; tan \; \alpha \; sin \; \alpha \; = \; 2 \, \frac{d}{cos \; \alpha}(1 \; - \; sin^2 \; \alpha) \; = \; 2 \; d \; cos \; \alpha$$

so the condition for constructive interference is:

$$m \; \lambda \; = \; 2 \; d \; n \; cos \; \alpha$$

if the medium between the plates has a refractive index, n,

Because light can undergo many reflections between the two plates, and light is transmitted through the second plate after each pair of reflections, a large number of interfering rays is produced. This gives the instrument very high resolution (analogous to having many slits/lines on a diffraction grating). The more internal reflections, the sharper the interference image and thus the better the resolution. The resolution can therefore be improved by increasing the reflectivity of the inner surfaces of the plates. The disadvantage of this is that the total light throughput will be reduced.

If the source is uniformly illuminated, focussing the emergent rays produces an interference pattern of circular rings centred on the optic axis of the system.

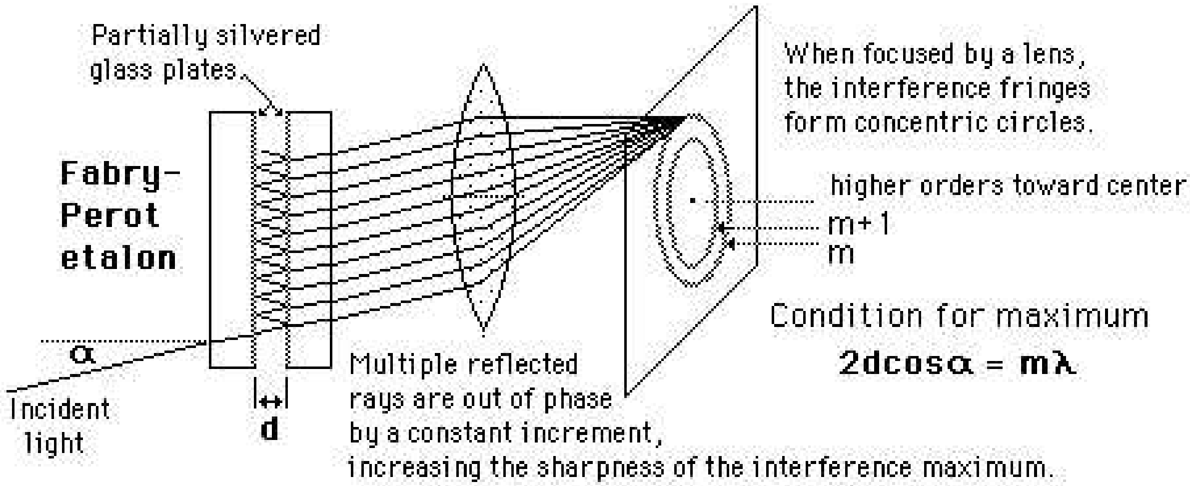


Figure 26: The Fabry–Perot interferometer.

As noted, the Fabry-Pérot interferometer has the advantage of high resolution (see the example of the sodium “D” lines doublet).

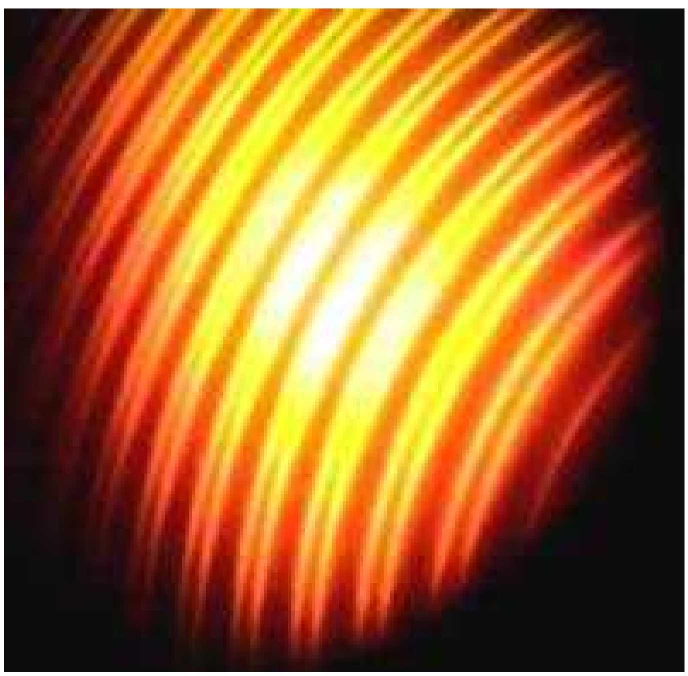


Figure 27: Sodium “D” lines through a Fabry-Perot interferometer.

Figure 28: Large (80mm) LightMachinery piezo-tunable Fabry-Pérot interferometer.

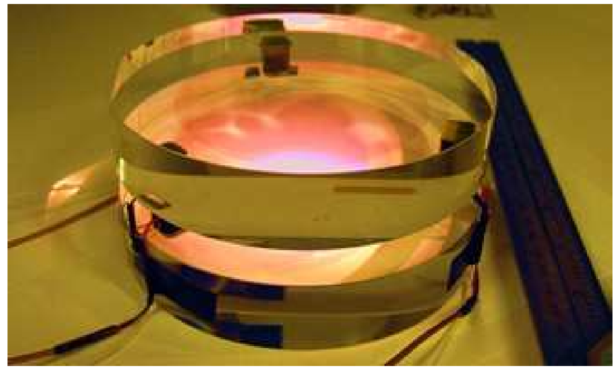


Figure 29: LightMachinery piezo-tunable Fabry-Pérot interferometer.

5.2 Free spectral range and Finesse

A couple of terms you might come across with respect to Fabry-Pérot instruments are **free spectral range** and **finesse**.

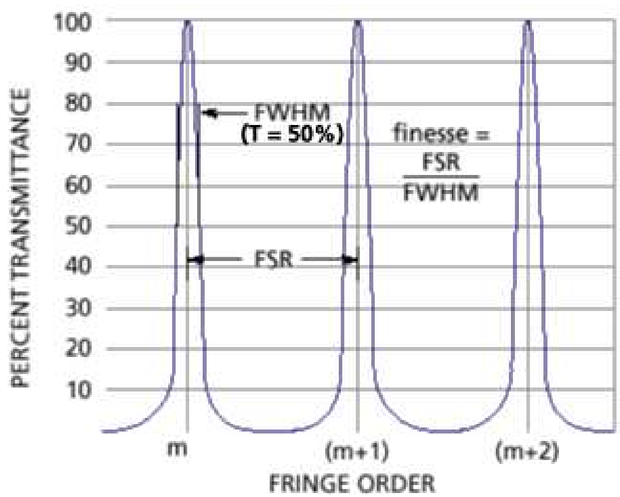


Figure 30: Definition of free spectral range and finesse.

The **free spectral range** (FSR) is the distance (in frequency space) between adjacent transmission maxima (orders) – see figure. It is a function of the separation of the interferometer plates. **Note that this is different from the definition of FSR for grating spectra**, though the concept is similar.

The full width half maximum (FWHM) of the transmission maxima is the same as the definition we have used elsewhere, though I have seen this referred to as **minimum resolvable bandwidth** in the Fabry-Pérot context.

The **finesse** of the interferometer is a figure of merit for the transmission bandwidth. It is defined simply by:

$$Finesse \quad = \quad \frac{FSR}{FWHM}$$

For a perfect etalon or interferometer (perfectly parallel plates, perfect optical surfaces, etc) the finesse is a function of the reflectivity, R, of the Fabry-Pérot plate surfaces:

$$Finesse \quad = \quad \frac{\sqrt{R}}{(1 \ - \ R)}$$

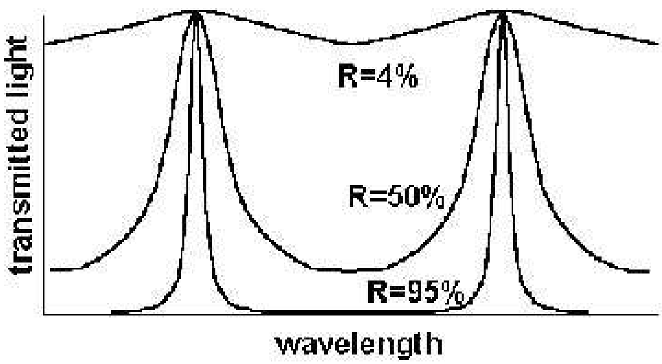


Figure 31: Increase of finesse (resolution) with increasing reflectivity of the Fabry-Pérot plates.

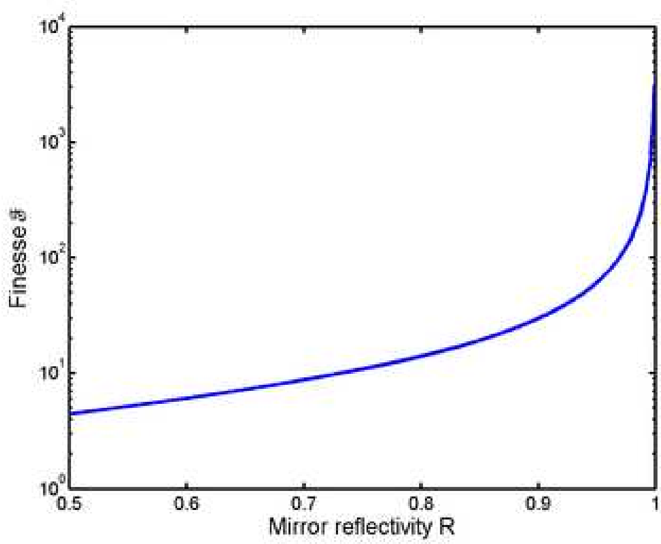


Figure 32: Increase of finesse (resolution) with increasing reflectivity of the Fabry-Pérot plates.

5.3 Astronomical use

In astronomical use, it is common to isolate a single line of interest, such as Hα, using a narrow passband interference filter – or even a second etalon.

One can think of the Fabry-Perot as being a tunable, very narrow passband interference filter. An image can be obtained at a certain separation of the etalon, then the passband changed by either varying the refractive index, n (eg by increasing or decreasing the gas pressure) or, more usually, by slightly moving one of the plates to alter the separation, d.

By doing this repeatedly, a three-dimensional picture of the image can be constructed – a "data cube" – where one of the dimensions is wavelength. Actually, one really has four quantities – x, y, wavelength and intensity.

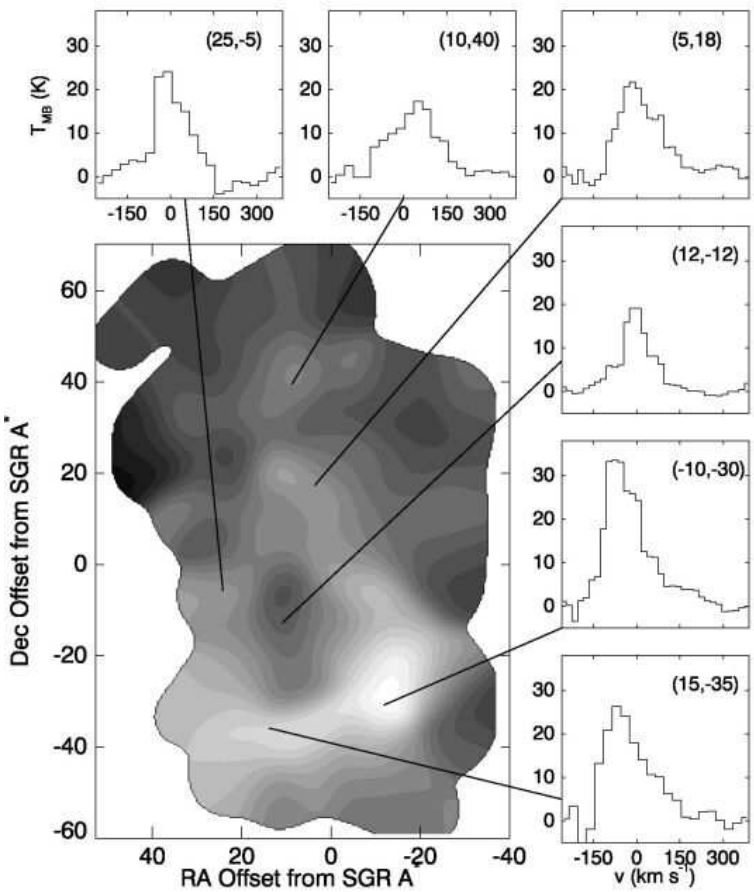


Figure 33: Sagittarius A measured with a Fabry-Perot.

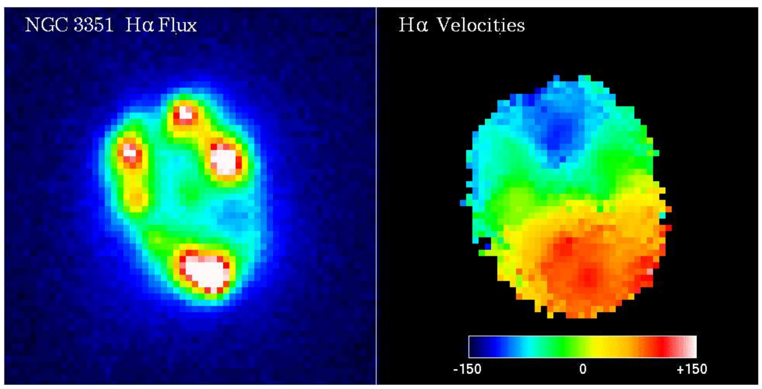


Figure 34: Galaxy NGC 3351. Left - intensity (in Hα); right - velocity field. From the Ohio Imaging Fabry-Perot Spectrometer.

6 Integral Field Spectroscopy

We have seen the concept of building a "data cube" – essentially an (x, y, λ) dataset – by using a Fabry-Pérot spectrograph. (It would even be possible to do a similar job using a long slit spectrograph and "stepping" across a field). These techniques do not allow simultaneous acquisition of the whole data cube – and that could be a problem; for example, to obtain a good data set with a Fabry-Pérot interferometer, it would be necessary to have good observing conditions during all of the consecutive measurements with different separation of the interferometer plates. Whilst this is by no means impossible, we now look briefly at integral field units (IFUs) which can acquire a data cube at one go. A lot of effort has gone into developing these over the past decade or so and some of the general concepts are shown in the figure.

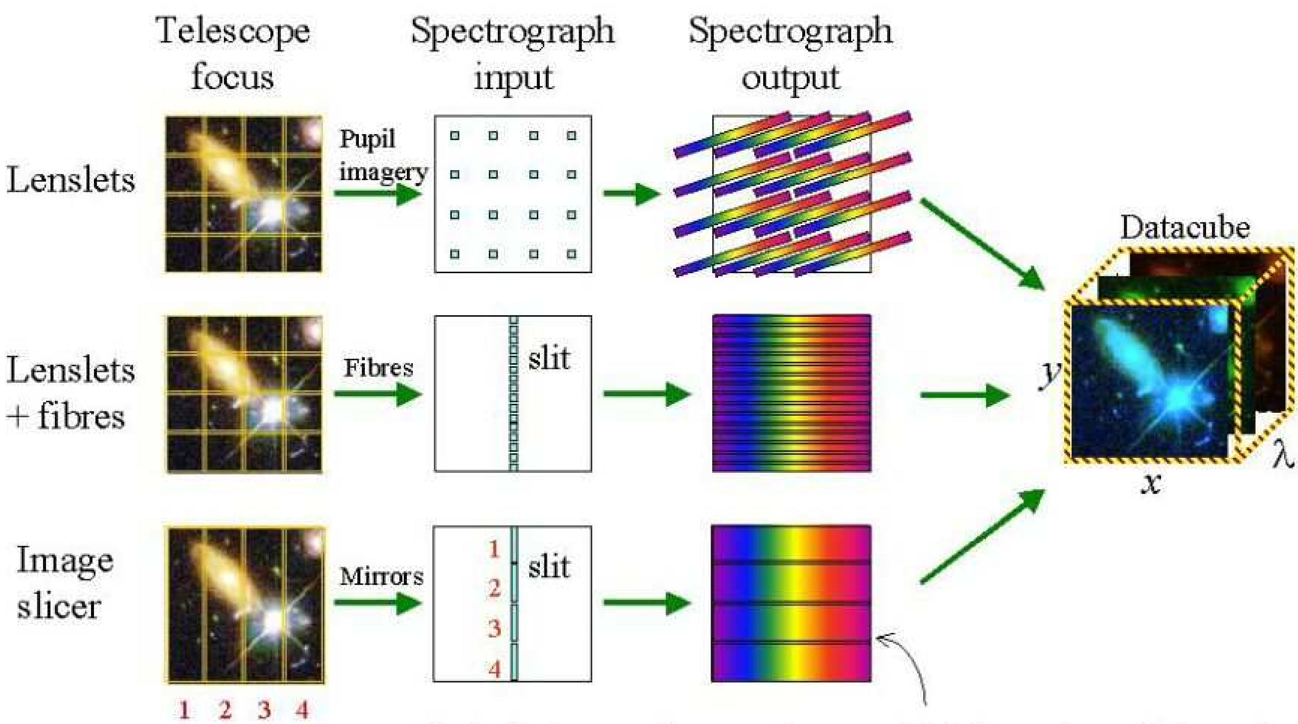


Figure 35: Basic ideas of integral field spectroscopy.

- The first scheme looks a bit like the Shack-Hartmann test except that instead of using a mask to produce small rays or cylinders of light, lenslets image the whole area by reducing small subdivisions (squares) into much smaller areas which are then input to the spectrograph. (So, actually nothing like the Shack-Hartmann test, really).
- We have already seen something similar to the second concept in the above figure – the 2dF on the Anglo-Australian Telescope and 6dF on the AAO Schmidt, where small right-angle prisms attached to optical fibres are used to pick off individual stars (about 400 in the case of 2dF and $\sim$ 120 in the case of 6dF. Again, in the case of the IFU, it's not a question of

picking out individual stars, but collecting all the light from the selected area (of an extended object). This is shown schematically in the next figure:

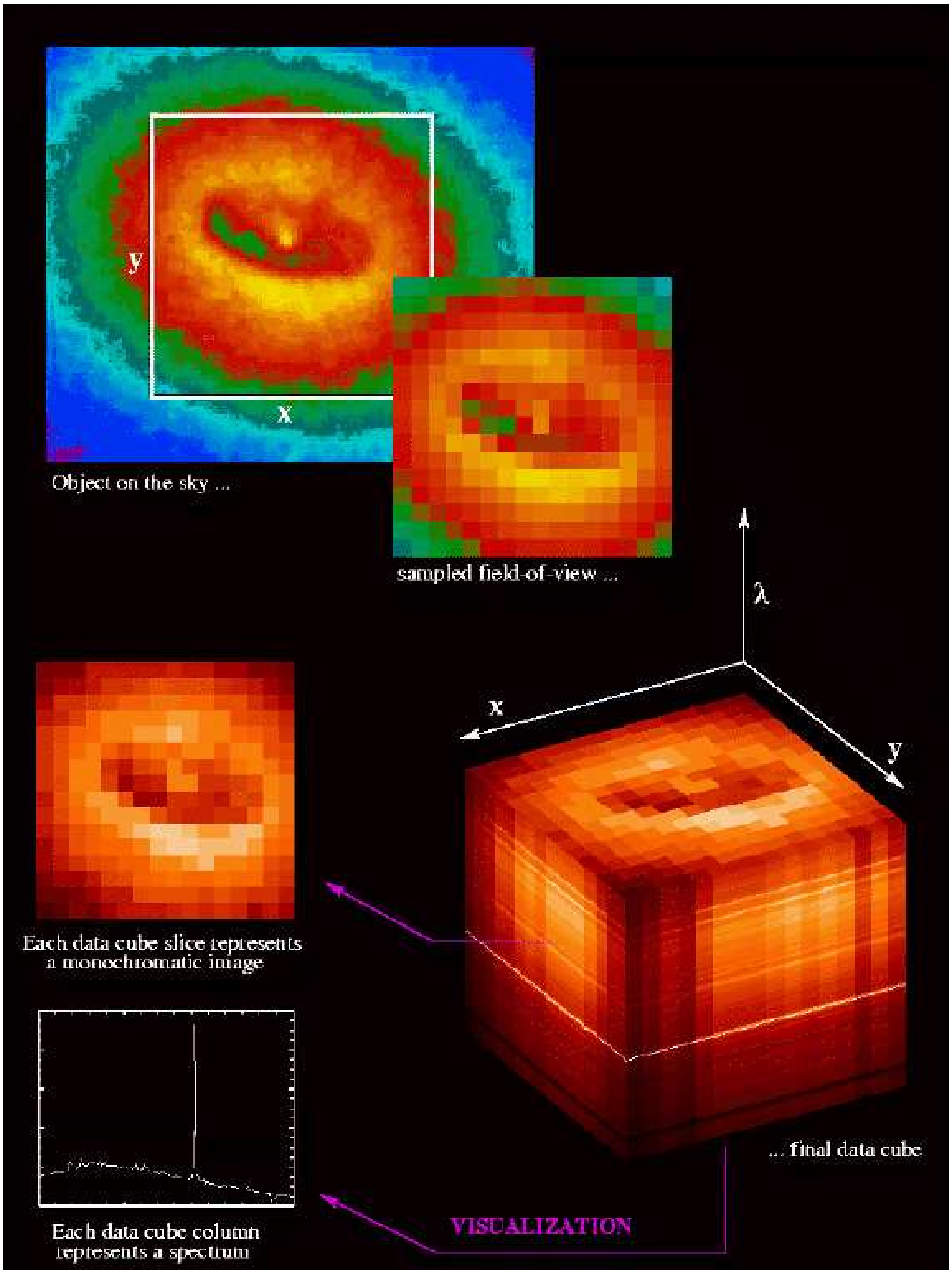


Figure 36: The data cube. A 2-dimensional field (white rectangle) ia sampled into discrete spatial elements (which need not be square). These are sometimes called **spaxels** - spatial pixels. The data cube can be sampled “horizontally” to give a monochromatic image of the source (or broader band images by co-adding “slices”) or can be sampled “vertically” to give spectra related to an (x, y) point.

• The third idea – using an "image slicer" to slice up the image and redistribute the light is worth looking at (because it is quite clever):

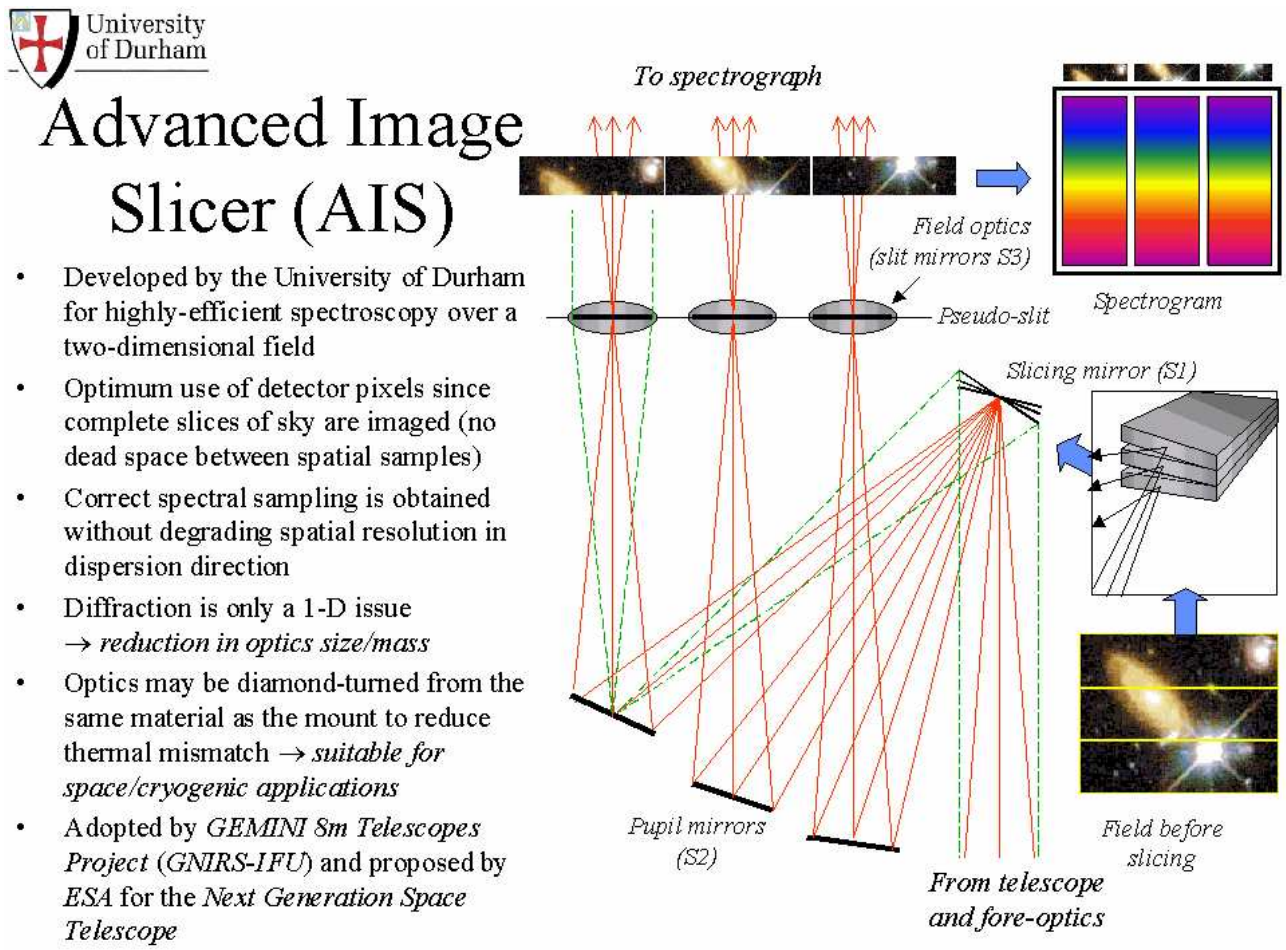


Figure 37: Durham University (UK) designed image slicer.

A little more detail for a couple of actual IFS systems is shown in the next two figures

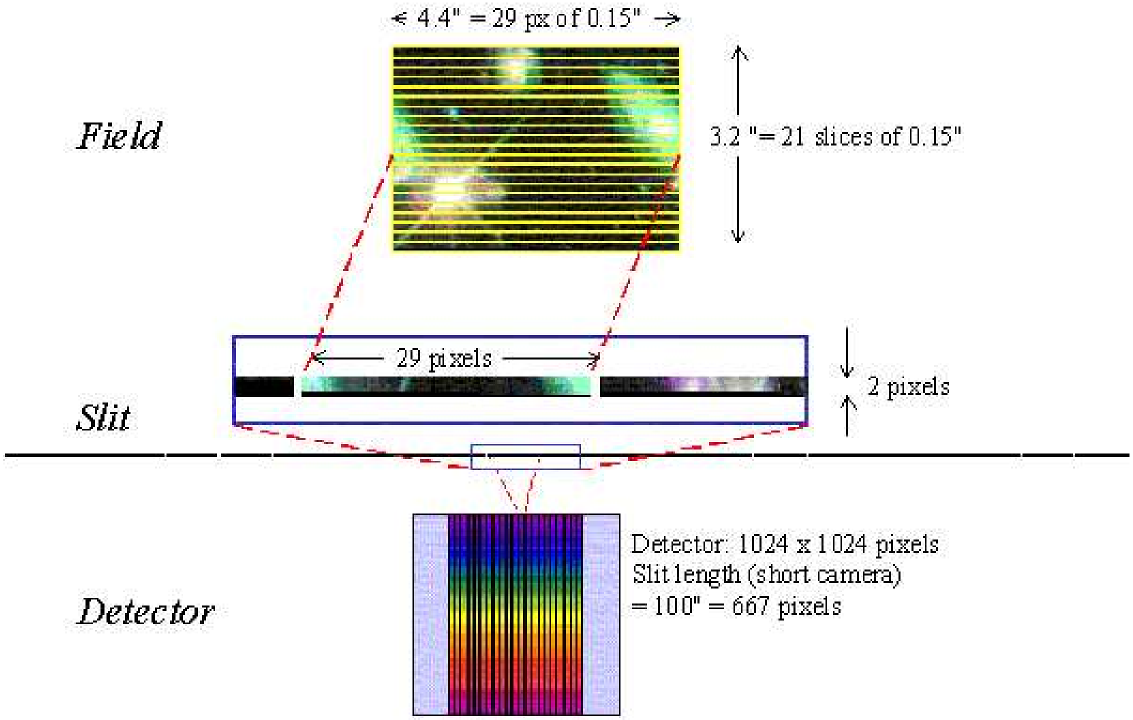


Figure 38: Schematic for the GEMINI Near Infrared spectrograph (GNIRS) – an image slicer system.

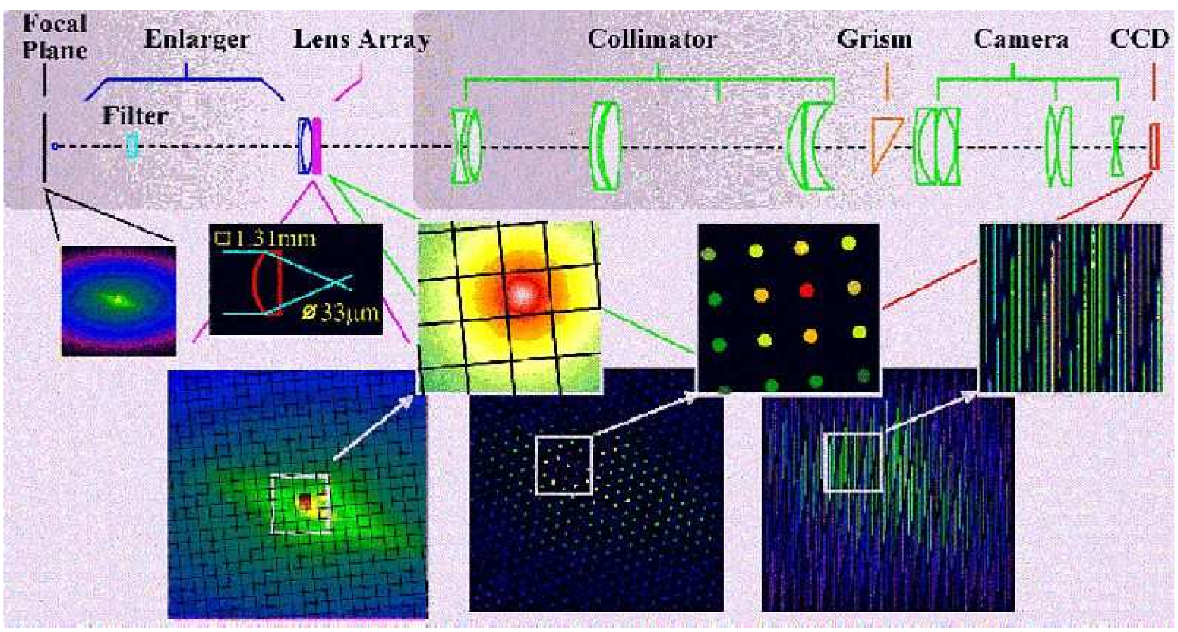


Figure 39: Schematic layout for SAURON – pupil imaging using a lenslet array. The filter selects the wavelength range and the enlarger images the sky on to the lenslet array. The collimated light is dispersed by a grism and a camera images the the spectra to a CCD.

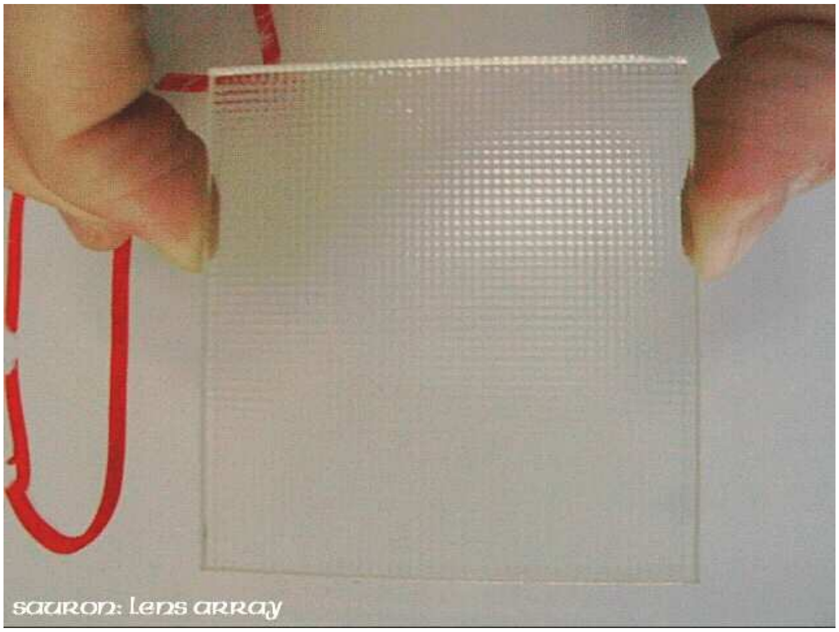


Figure 40: The lenslet array for SAURON – over 1600 square lenslets, each about 1.35mm square. Each lenslet images about 0.94 x 0.94 arcsecs, giving a fully covered field of about 33 x 41 arcsecs – "one eye that sees all".

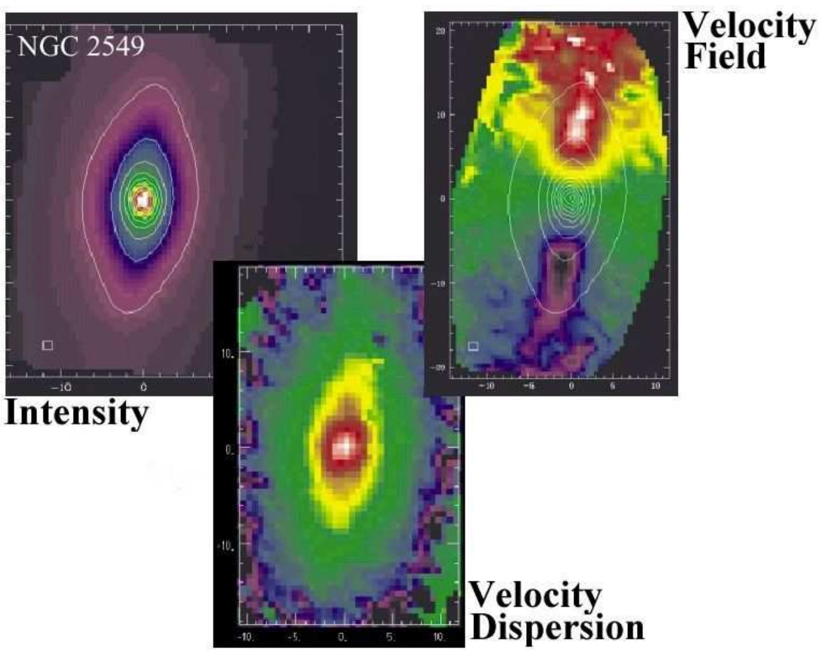


Figure 41: Early data from SAURON.

More details on SAURON, GNIRS and other IFS applications together with some useful links can be found on the Durham University web page at aig-www.dur.ac.uk