Spectroscopy and Spectrophotometry

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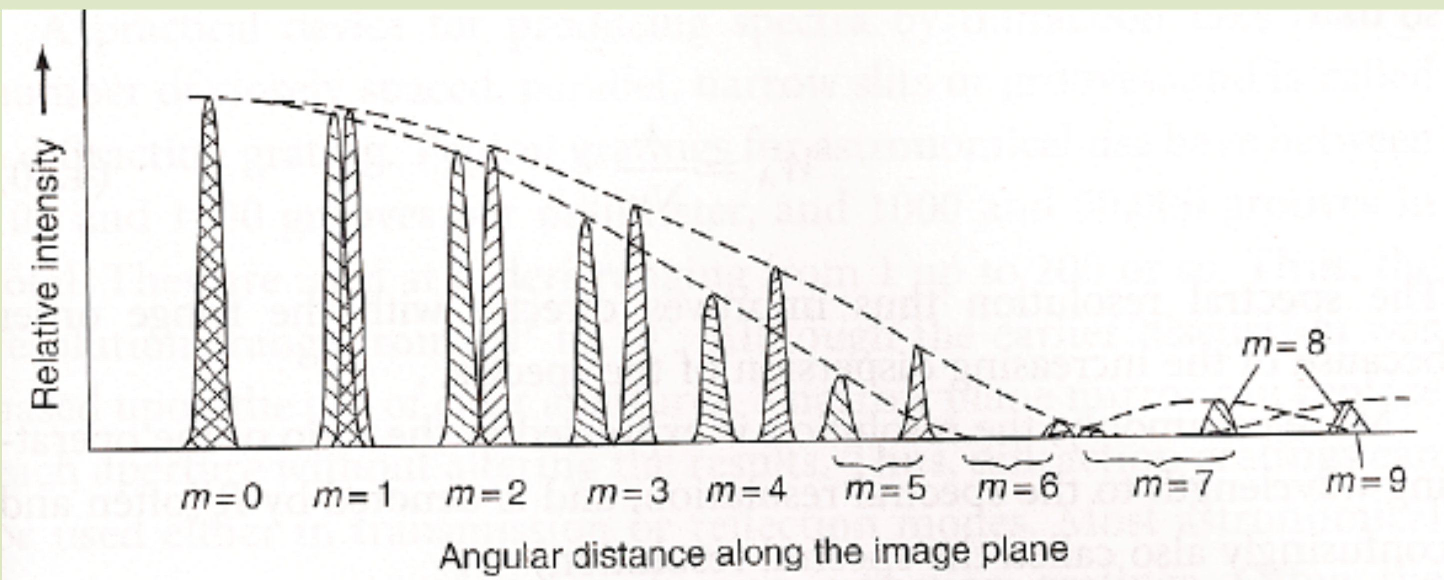
Outline

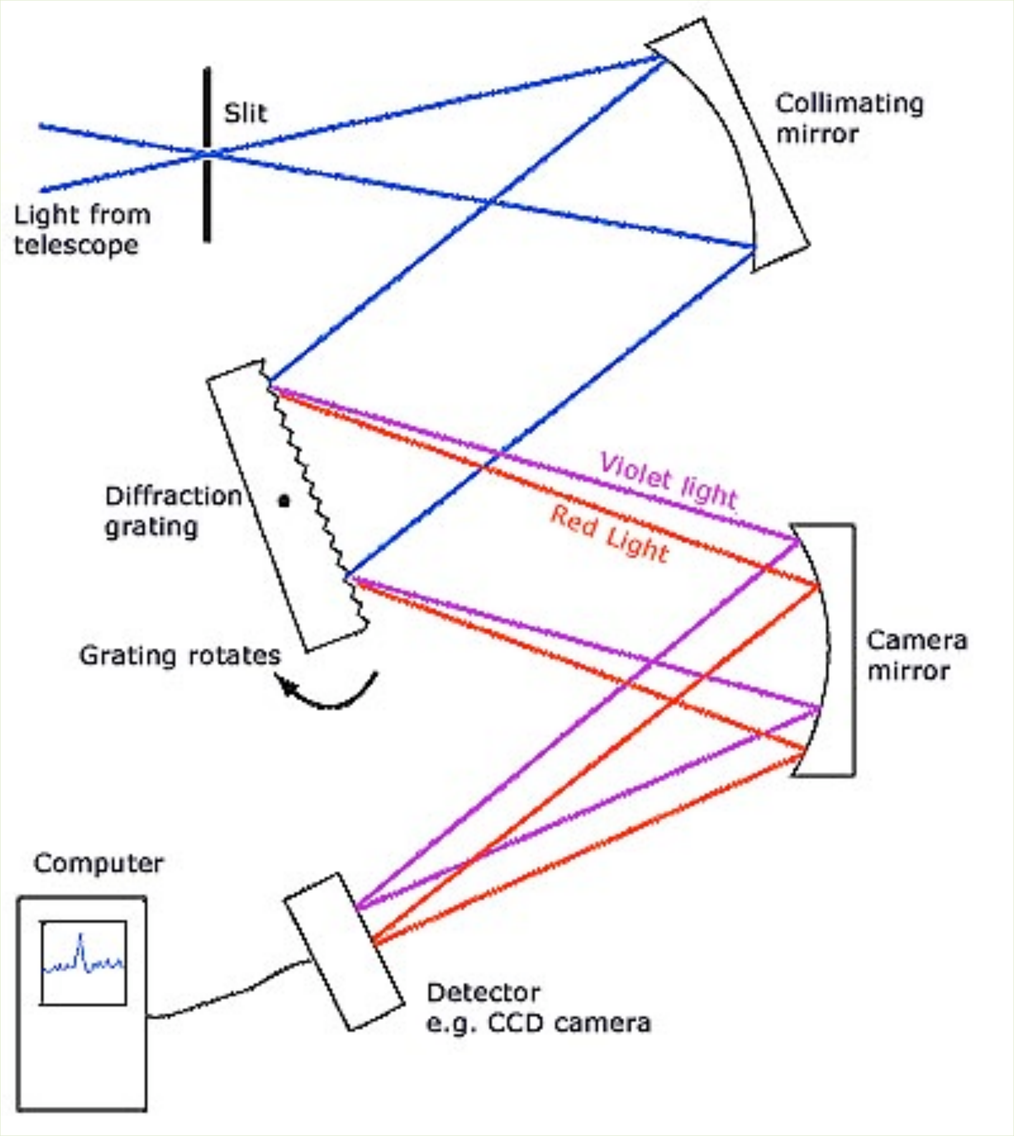
- Basic elements of spectroscopy
  - Mathematics of spectrometry
  - Basic components of a spectroscope
  - Utilizing CCDs effectively
  - Calibrating the wavelength scale
  - Calibrating fluxes
- Case study: the Harps spectrograph
- 1D and 2D spectroscopy
  - Long-slit and integral field spectroscopy
  - Fiber spectroscopy

Spectrometry Review

- Monochromatic light of wavelength λ is incident on a grating with N apertures each of width D and separated by a distance d. The light diffracts into equally spaced sinc functions (called "orders") modulated by an "envelope" sinc function.
- Each order has angular width $W \sim 2\lambda/Nd$ and the angular separation between orders is $\sim 2\lambda/d$. Different frequencies are separated because the location of an order depends on λ



Classical Spectroscope Design



Design Considerations: The Slit

- Old-fashioned common sense says that the slit should be wide enough to capture all the light from the object. For a point source $s \sim 2\ \mathrm{FWHM}$
- However, if the slit is too wide, it compromises the resolution of the system. Roughly speaking, the slit should be no wider than the diffraction limit of the spectroscope $s \lesssim f_{coll}\lambda/L$
- If $2\ \mathrm{FWHM} \gtrsim f_{coll}\lambda/L$, we have a problem.

Note: $L = Nd$

Design Considerations: Resolution

- In order to find the center of a line in a spectrum, we need to fit a profile to it.
- In order to fit a profile, each line must spread over a few pixels of the CCD.
- Since CCDs have a spacing between pixels of ~15 microns, this means $W \sim 50\mu\mathrm{m}/f_{im}$
- We can then deduce the resolution

$$(W/\lambda) d\lambda/d\theta = \Delta\lambda/\lambda =$$

$$10^{-5}\left(\frac{l_{CCD}}{50\mu m}\right)\left(\frac{10}{F}\right)\left(\frac{1m}{L}\right)\left(\frac{500mm^{-1}}{R}\right)\left(\frac{3}{m}\right)\left(\frac{500nm}{\lambda}\right)$$

Utilizing CCDs Effectively

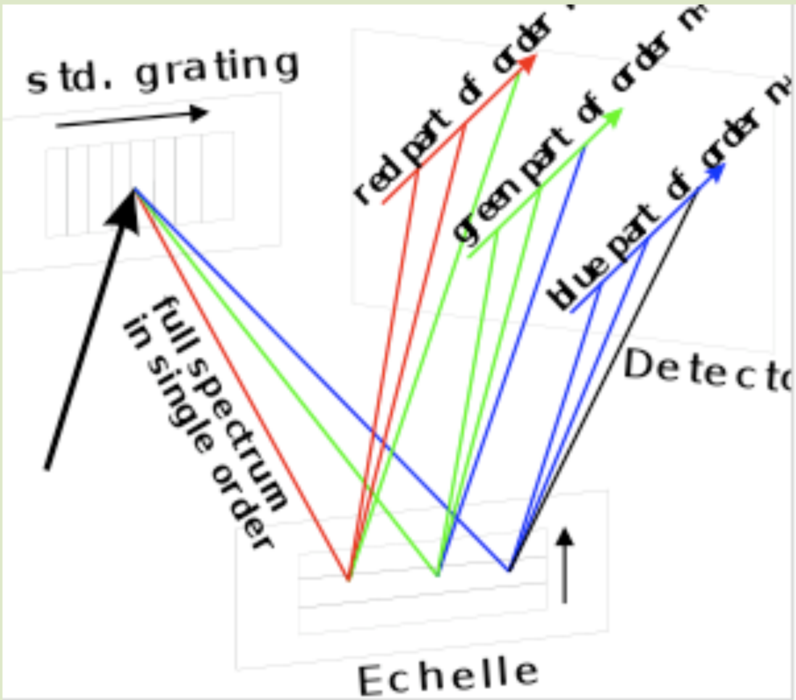
- Gratings produce linear images, but CCDs are roughly square. What do we do?
- Answer #1: Do nothing. What is the wavelength range that fits on the CCD?
- A CCD has ~4096 pixels. Throw in a factor of sqrt(2) if we take the spectrum across the diagonal, so spectrum is ~6000 pixels across.
- $\Delta\lambda/\lambda \sim 10^{-5} \sim 3 \text{ pixels}$ so at $\lambda = 500 \text{ nm}$ the spectral range across the CCD is only 10 nm

Utilizing CCDs effectively cont.

- Answer #2 use an echelle spectrograph. In an echelle, we first create a “normal” 1D spectrum at low order (m ~ 2). This spectrum is then split again (perpendicularly) using an echelle grating. The echelle creates a spectrum at high order (m ~ 50). At such high m, we have overlapping of neighboring orders. The CCD image then consists of ~50 vertically displaced orders. The spectral range is thus increased by a factor of ~50 from before.
- Got all that? If not, just wait one moment.

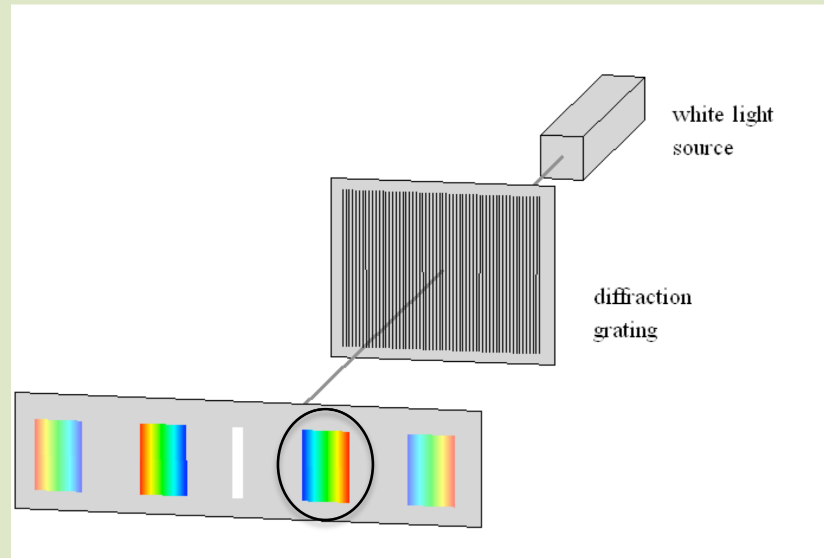
Echelle Spectrometer Basics

Echelle Design



Notice the echelle is ruled perpendicularly to the std. grating. This is the key.

Effect of the std. grating

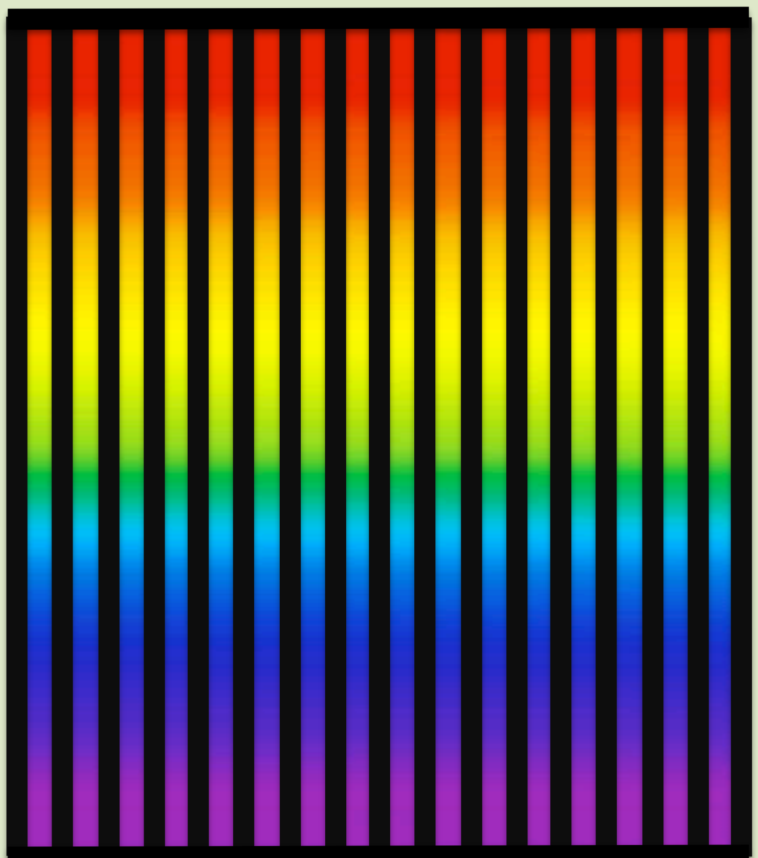


The std. grating is optimized so that most of the light is in a given low order (e.g. first order). This light then falls on the echelle.

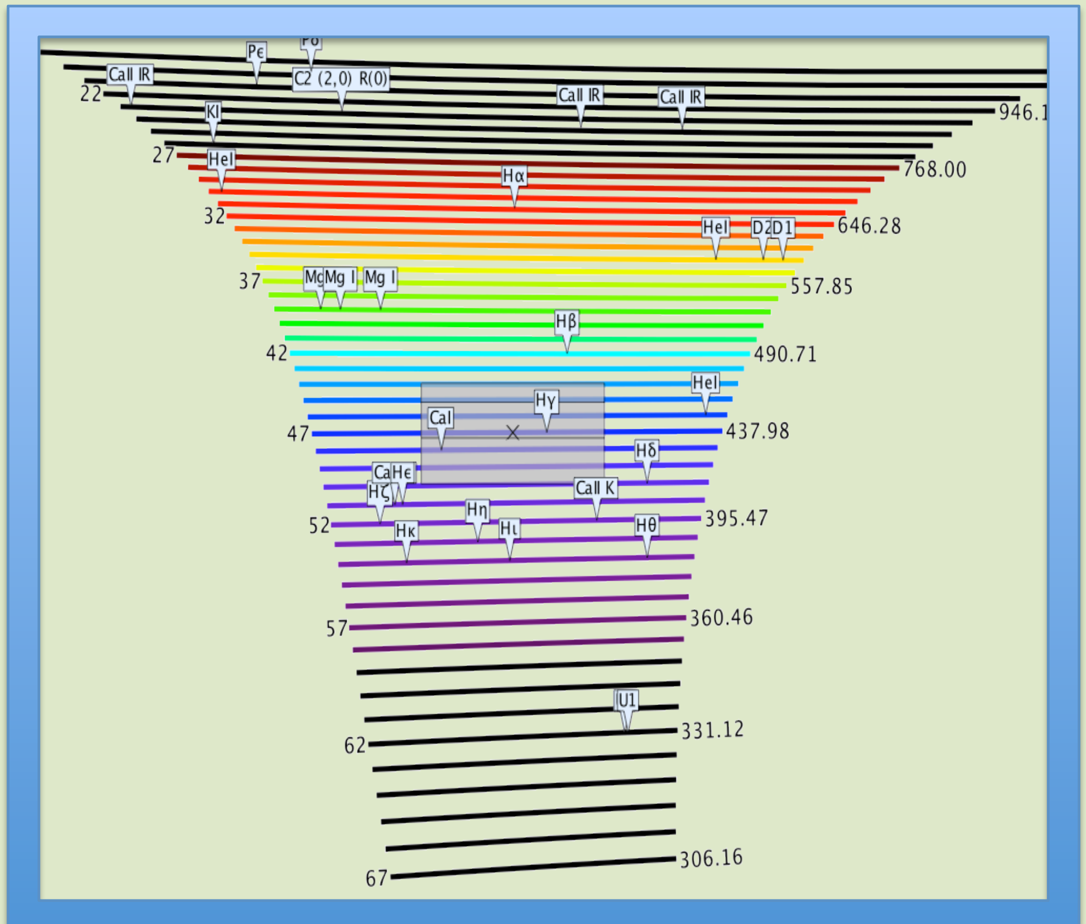
The Echellogram

The angle between the echelle and the CCD is optimized for high orders. The overlap of the orders is the key to the echellogram.

On the Echelle



On the CCD



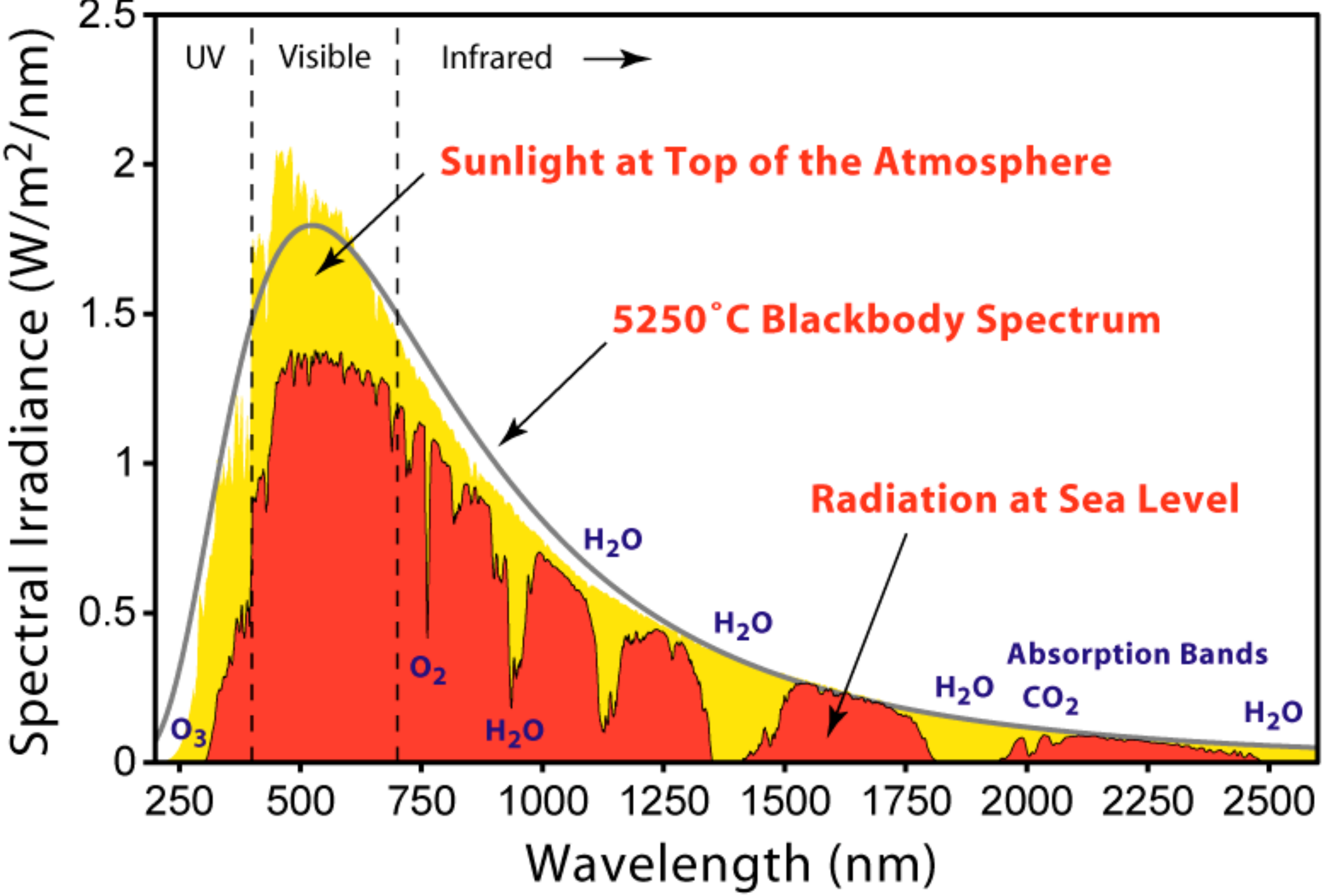
Calibrating the Wavelength Scale

- Typically a reference spectrum is used.
- In absorption, an iodine cell is placed between the grating and the slit. The imaged spectrum thus has iodine absorption features.
- In emission a second reference spectrum is generated that is spatially separated on the CCD e.g. using a Thorium lamp.
- A new technique being considered is to use a femtosecond laser to generate a series of short pulses at regular intervals (effectively a Dirac comb). This creates a uniform “ruler” in frequency space as the Fourier transform of a Dirac comb is also a Dirac comb.

Calibrating Fluxes (Spectrophotometry)

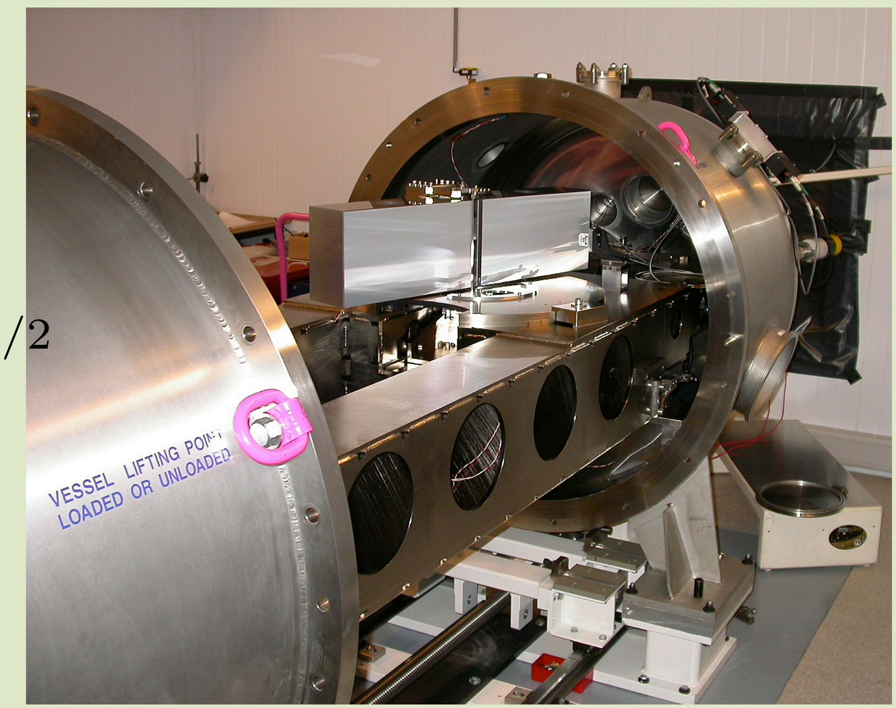
- Basic idea:
  - Measure the spectrum of a reference star near the source.
  - Generate a model spectrum for the star. Normalize the it to give the same broadband flux as the reference star.
  - Divide the observed spectrum of the reference star by the model spectrum. Call this ratio $R(\lambda)$
  - The flux-calibrated spectrum is then given by $f(\lambda) = \dfrac{f_0(\lambda)}{R(\lambda)}$
- Pitfalls:
  - For a strong atmospheric absorption line, $R(\lambda) = 0$
  - If the star has strong spectral features it is impossible to calibrate at these wavelengths. This is especially problematic if the source has lines at these wavelengths also.
  - Atmospheric absorption varies in time and space. The reference star must be nearby to the source and must be monitored often.

Solar Radiation Spectrum



Case Study: Harps Spectrograph

- The HARPS spectrograph (echelle type) is on the 3.6 m telescope in Chile. It is used to measure stellar radial velocities down to a precision of 1 m/s, and has discovered ~75 exoplanets to date.



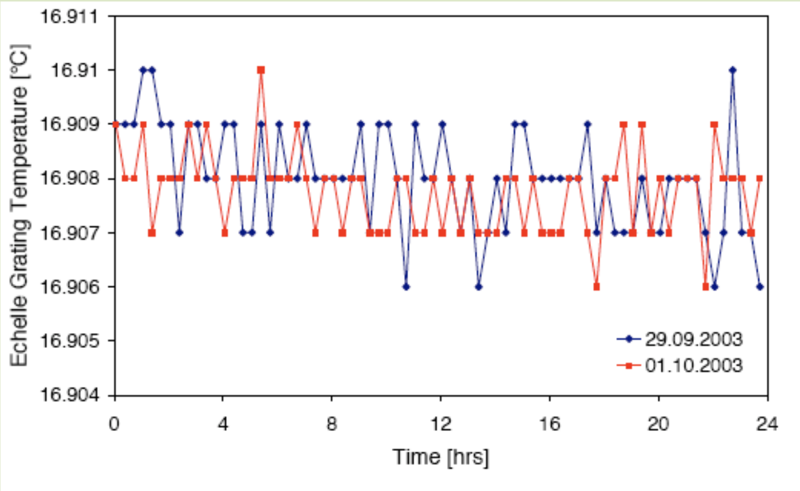
$$v \sim .09\frac{m}{s}\ \left(\frac{M_p}{M_e}\right)\left(\frac{M_\odot}{M_\star}\frac{1\mathrm{AU}}{R_p}\right)^{1/2}$$

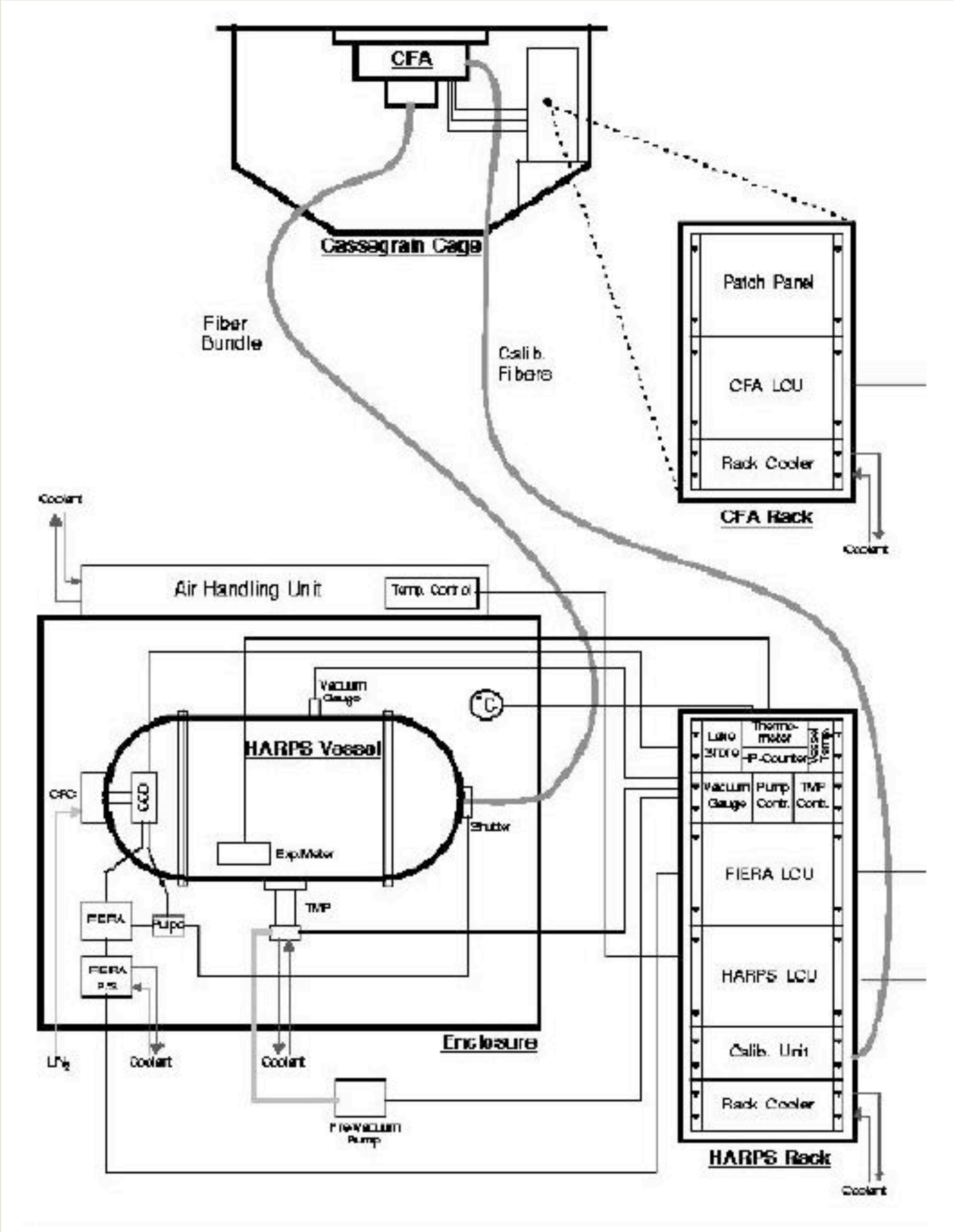
HARPS parameters

Table 1. HARPS spectrograph characteristics

Optical design	fibre-fed, cross-dispersed echelle spectrograph
Technique	simultaneous Thorium Reference
Number of fibres	2
Fibre diameter on sky	1 arcsec
Collimated beam diameter	208 mm
Spectral range covered	380 nm to 690 nm
Spectral resolution	RS =115'000
Spectral format	72 echelle orders 61.44 x 62.74 mm^2
CCD chip	mosaic, 2 x EEV 2k×4k pixel size = $(15\,\mu m)^2$
Sampling	3.5 pixels/spectral element
Minimum inter-order separation	30 pixels

HARPS Design





HARPS Radial Velocities

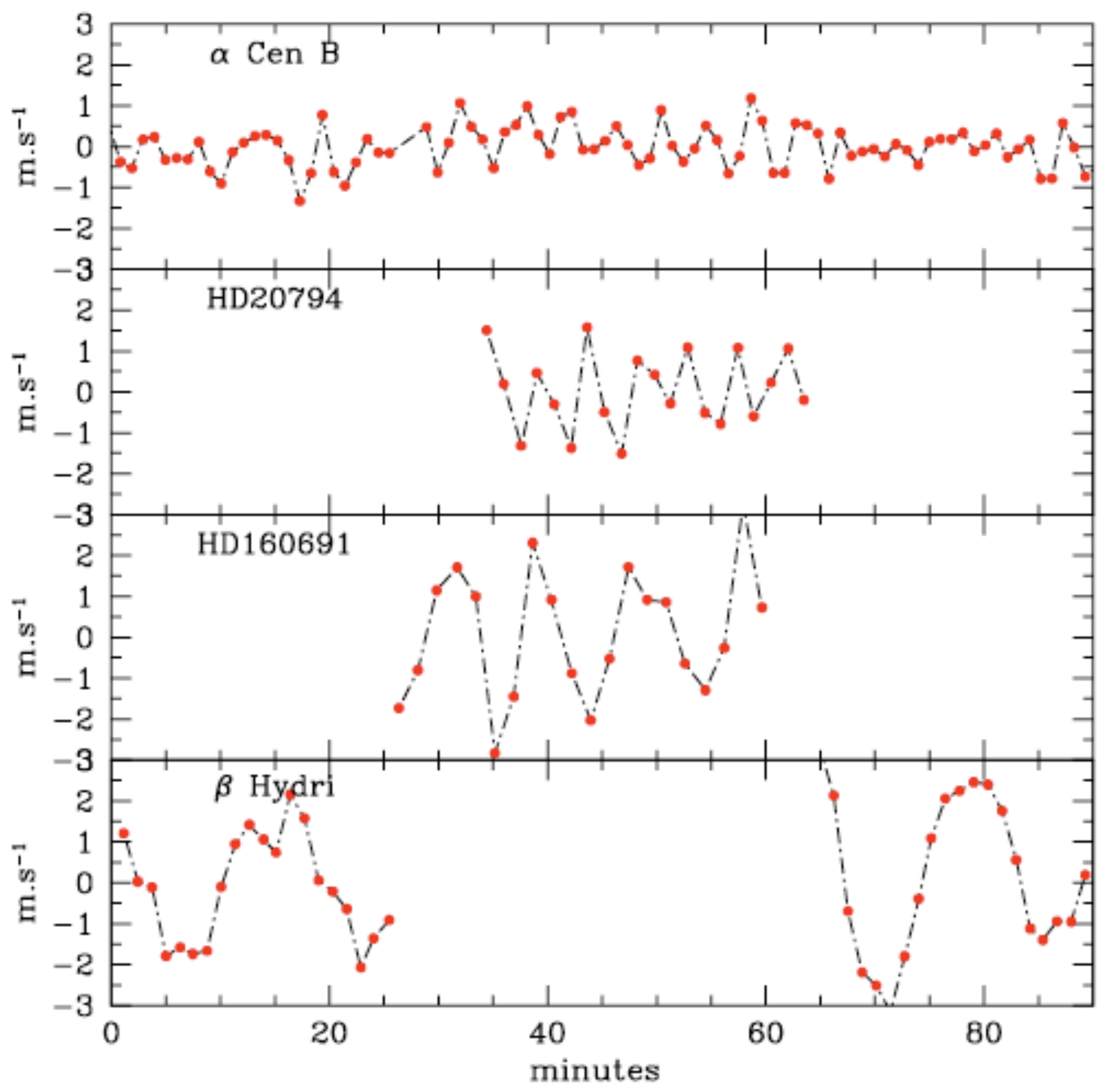
Question: What is wrong with this argument?

$$\Delta\lambda/\lambda = 10^{-5}$$

$$\Delta\lambda/\lambda = v_{min}/c$$

Therefore,

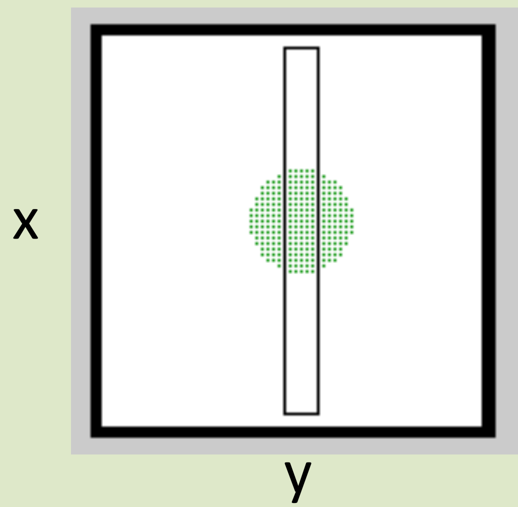
$$v_{min} = 3 \times 10^3 m/s$$



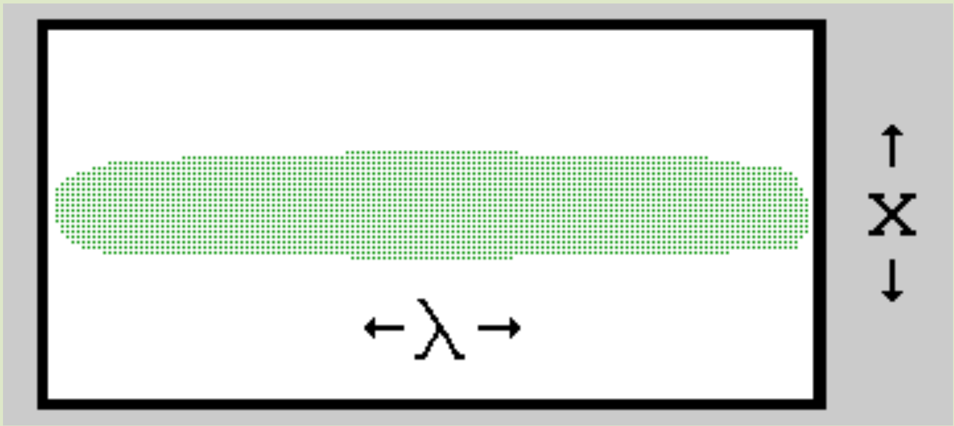
Long-Slit Spectroscopy

- The Echelle spectrograph allows the utilization of the whole CCD for measuring spectra.
- Another way to use the CCD area effectively is to let one direction be spatial information and the other wavelength information.

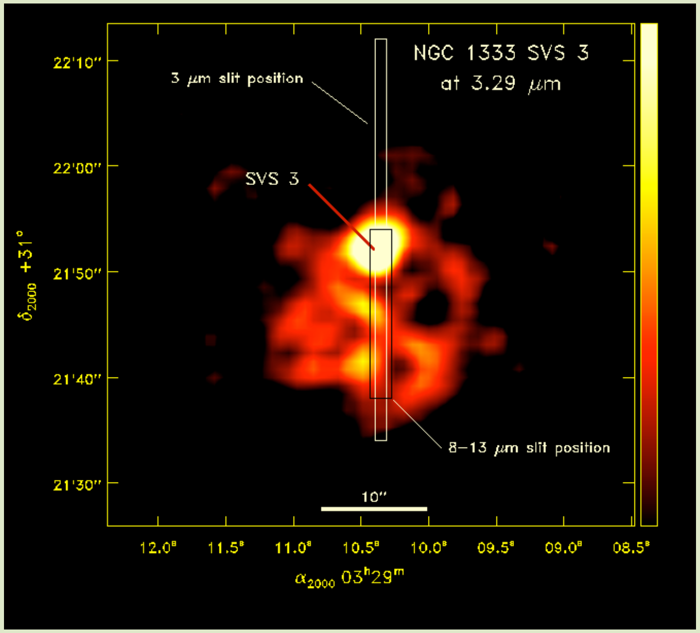
Focal plane of telescope

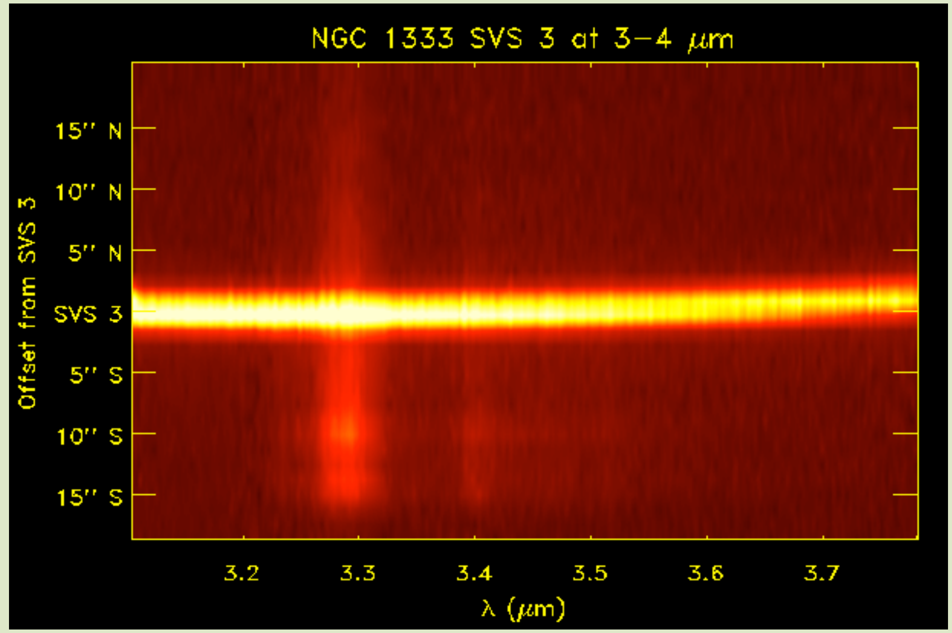


Focal plane of spectrograph

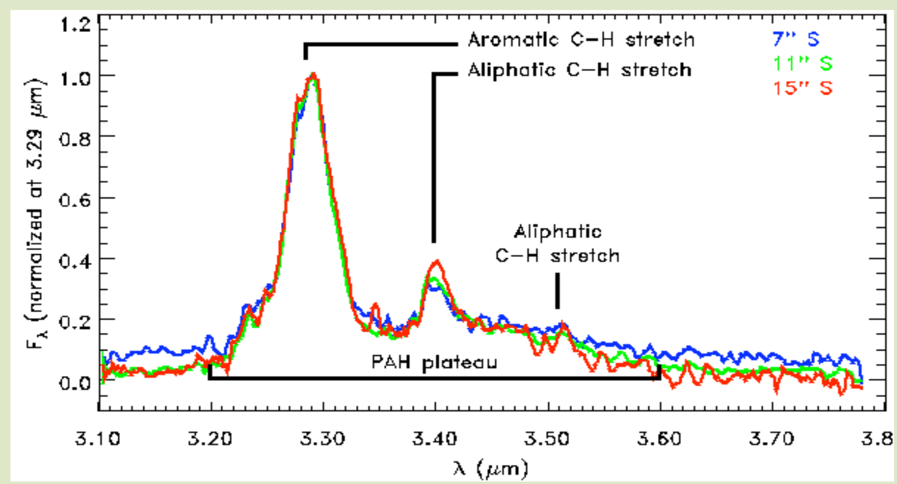


Long-Slit Spectra



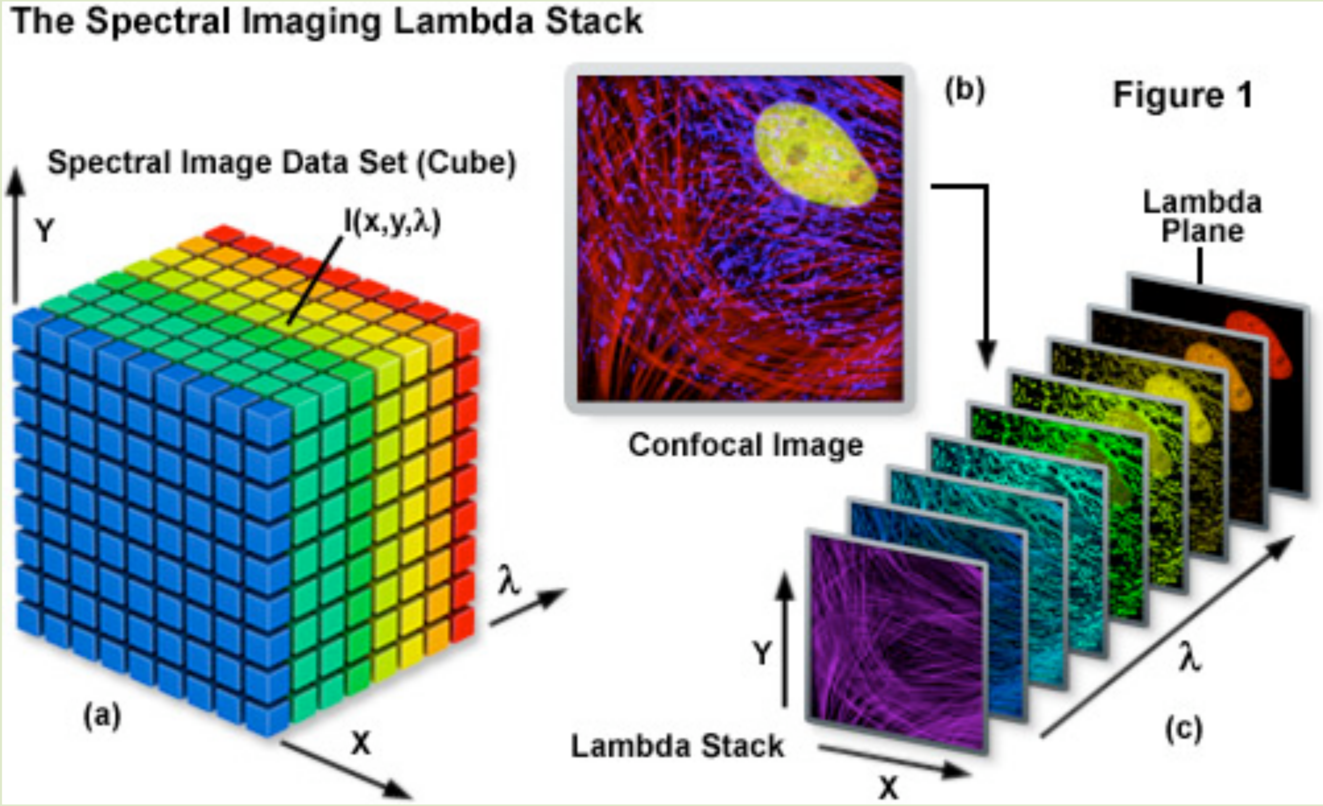


Emission from PAH molecules heated by a B-star in a molecular cloud.



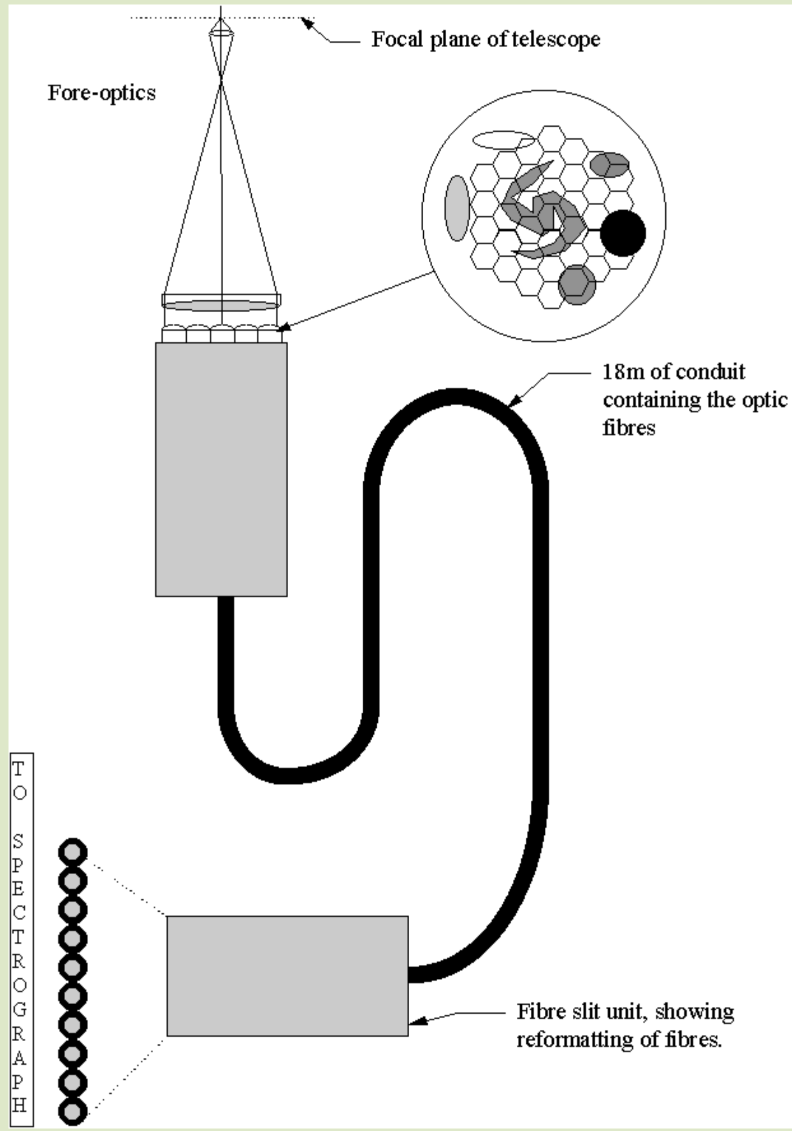
Integral Field Spectroscopy

- Same idea as long slit spectroscopy, but now we have a "spectral cube" of data, i.e. $\lambda(x, y)$



How IFS Works

- Optical Fibers are arranged in the focal plane of the telescope. They are rearranged linearly mimicking a slit before the collimator.
- Example: SPIRAL instrument on AAT.

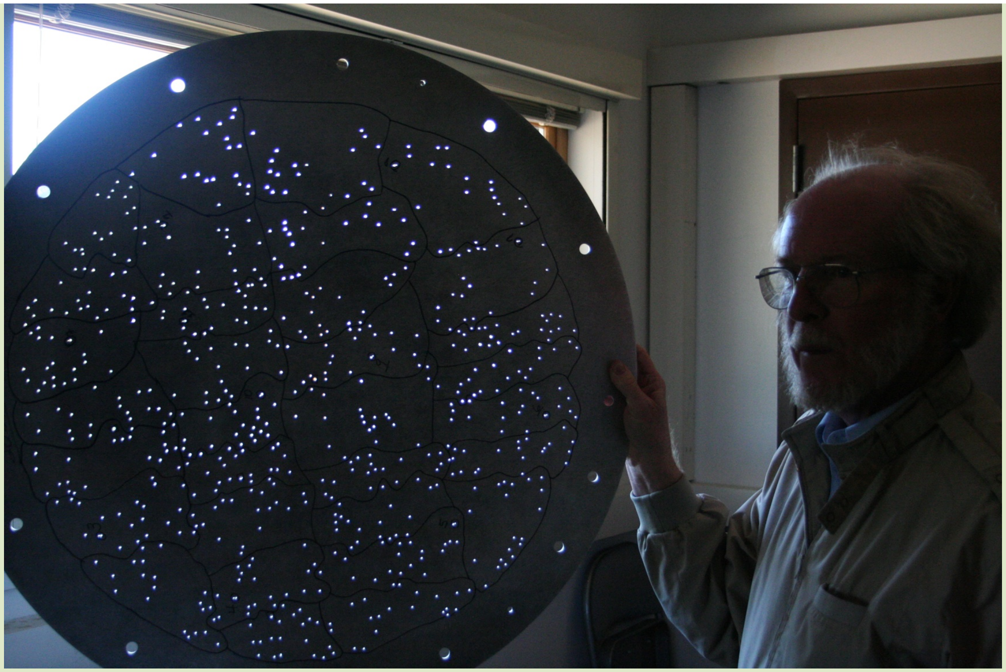


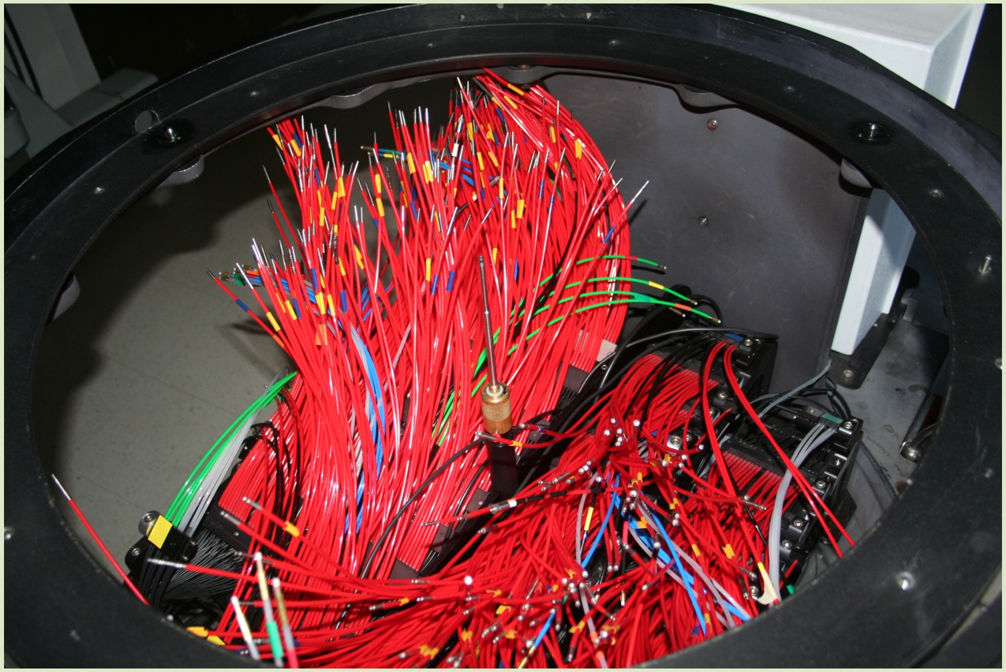
Multi-Object Spectrography

- Put optical fibers at the locations of objects in the focal plane of the telescope.
- Optical fibers feed into the spectrograph, creating a series of spectra in x, separated in y. This is similar to echelle, but spectra are now of different objects.
- Because objects move through the sky, fibers must be rearranged during the course of a night. Several strategies exist for doing this.

Plug Plates (SDSS)

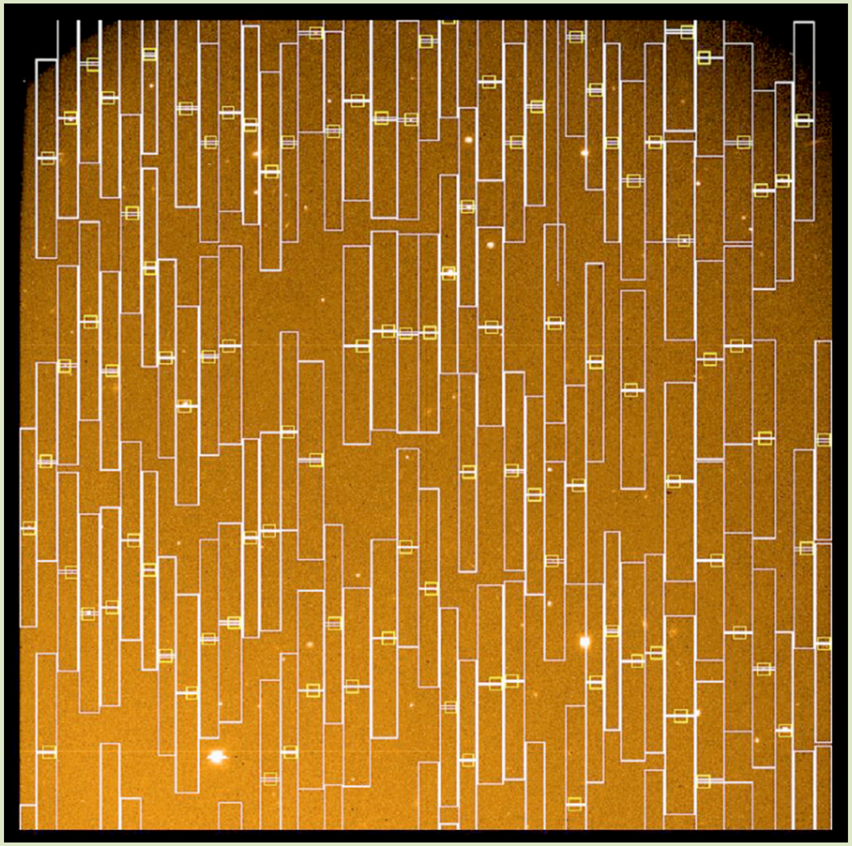
A plug-plate with holes representing the positions of objects in the field is inserted in the focal plane of the telescope. The plate is then plugged with optical fibers that go to the spectrograph.





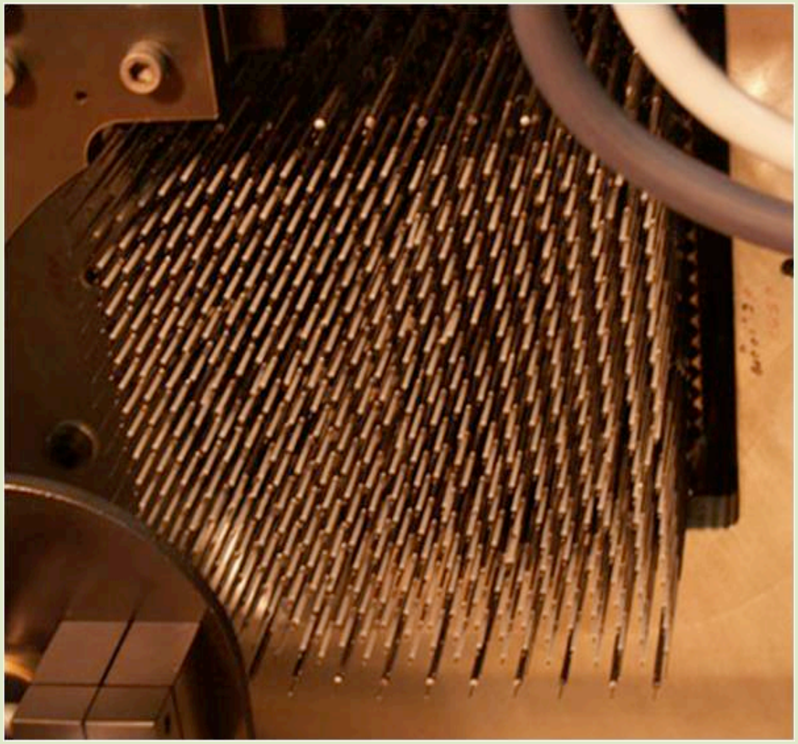
“Slit-Plates” (Gemini)

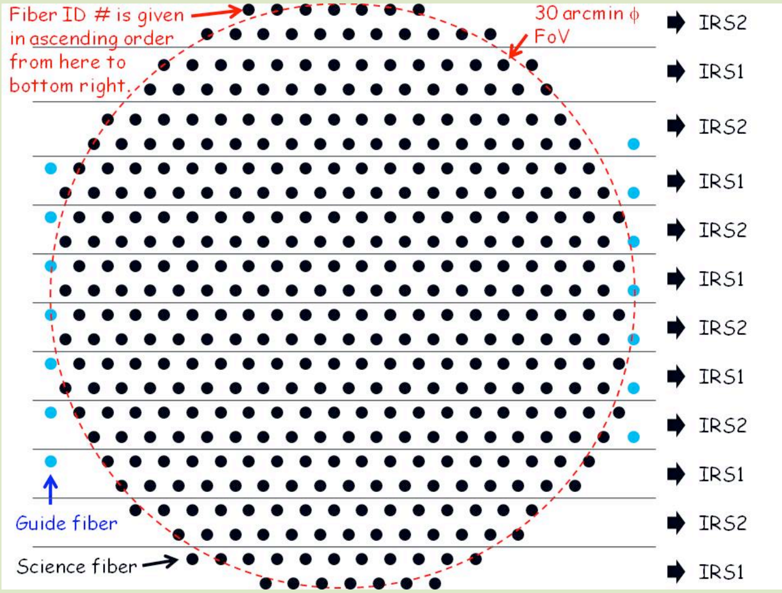
- Similar to plug-plates but no optical fibers. Just a plate with slits cut in it that shine directly on the collimator.
- Advantages over Fibers
  - Perfect transmittance
- Disadvantages
  - Small FOV
  - Overlap of spectra



Echidna System (Subaru)

- The instrument consists of a series of spines that can be positioned mechanically in the focal plane of the telescope. Each spine contains an optical fiber that goes to the spectrograph.
- Advantages
  – No plates to cut
- Disadvantages
  – Expensive





Summary

- Slit Size and Resolution are implicitly set by the other parameters of the spectroscope.
- Spectra are linear. To utilize the CCD area effectively it is necessary to use an echelle spectrograph or to do multi-D (long-slit/IFS) or multi-object spectroscopy.
- Multi-object spectroscopy can be done with optical fibers or slit-masks.
- A reference spectrum is used to calibrate spectrographs either in transmission or absorption.
- A reference star nearby to the source can be used to calibrate the flux, but atmospheric lines and lines in the source make it difficult.


Questions?
Vicki Tyley 2009