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INTRODUCTION TO OPTICAL OBSERVATIONS

Spectroscopy

Outline

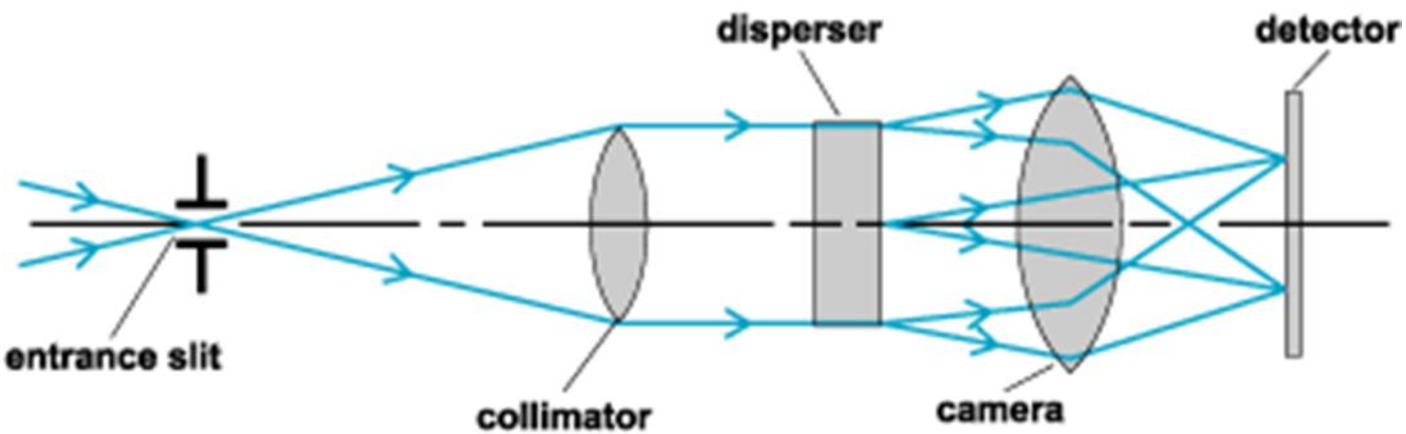
1. General introduction to spectroscopy
2. Practical spectroscopy
3. Spectral reductions (calibration)

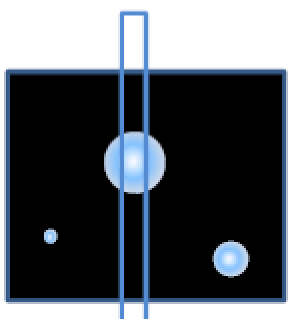
Spectroscopy

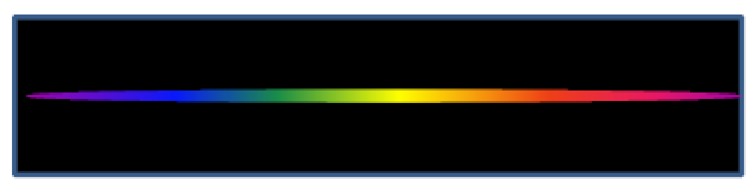
Spectral analysis is the source of most of our astrophysical knowledge.

Spectrometers

- All spectrometers have essentially the same basic design, but many different implementations are possible depending on the constraints and choice of spectral disperser.

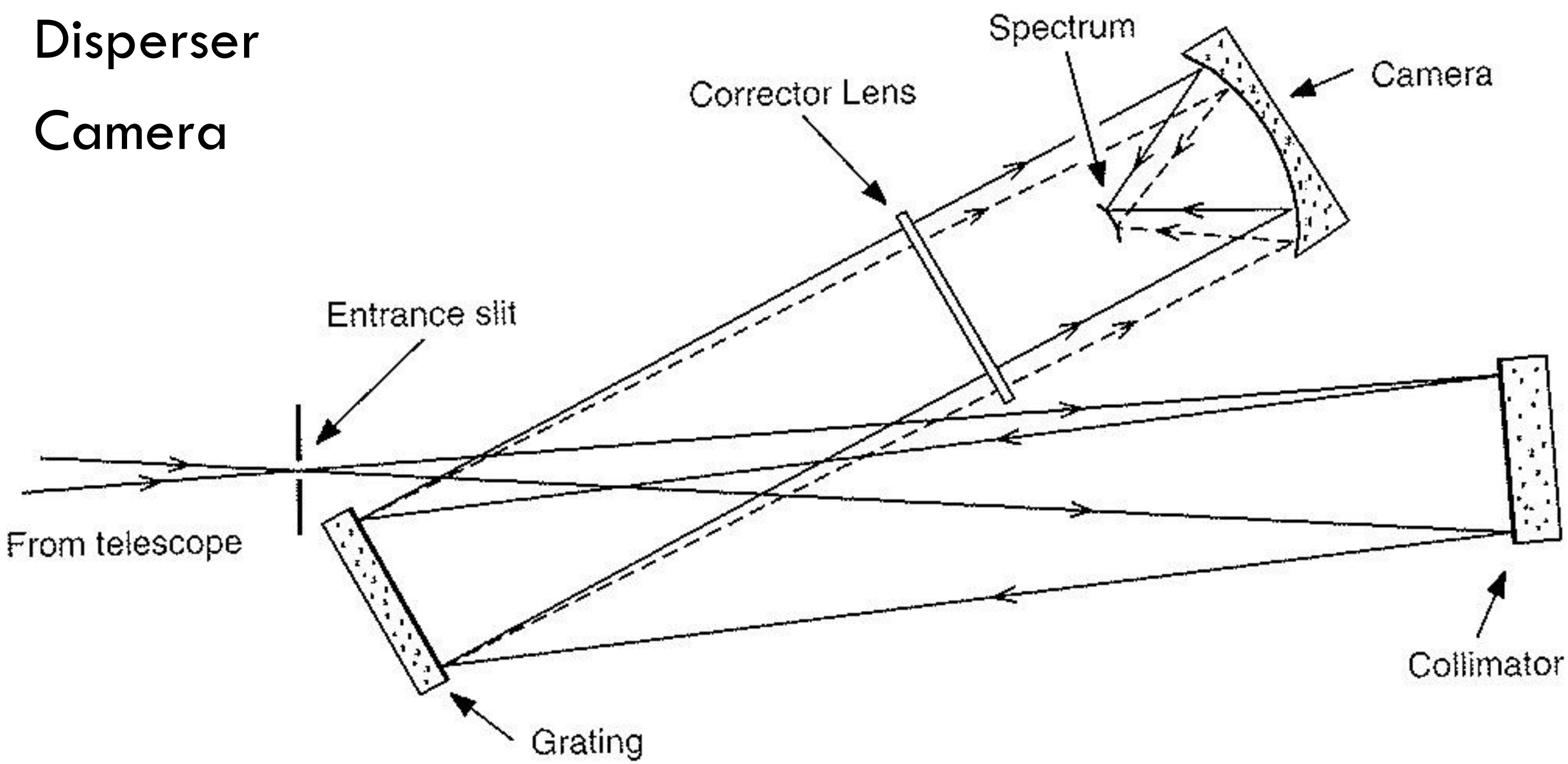






Spectrometers: main elements

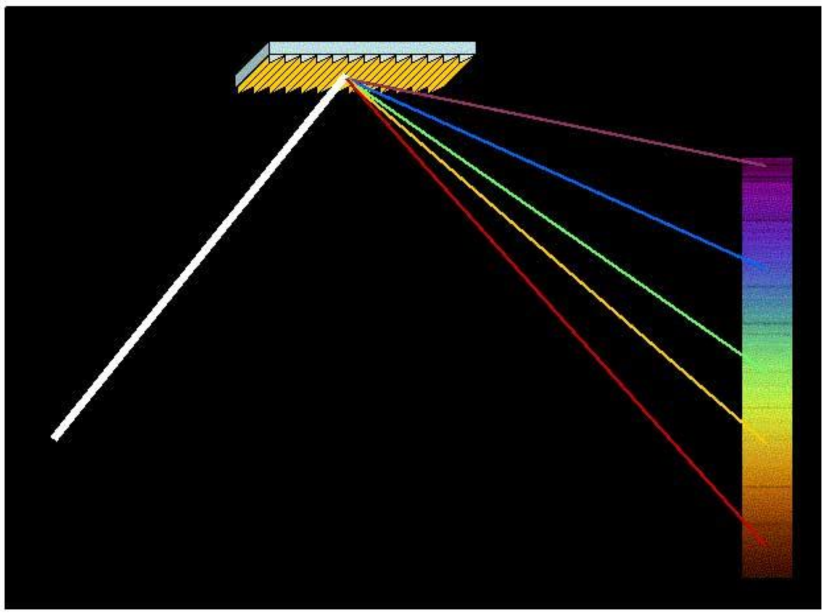
- Entrance apertures at focal plane of telescope
- Collimator
- Disperser
- Camera

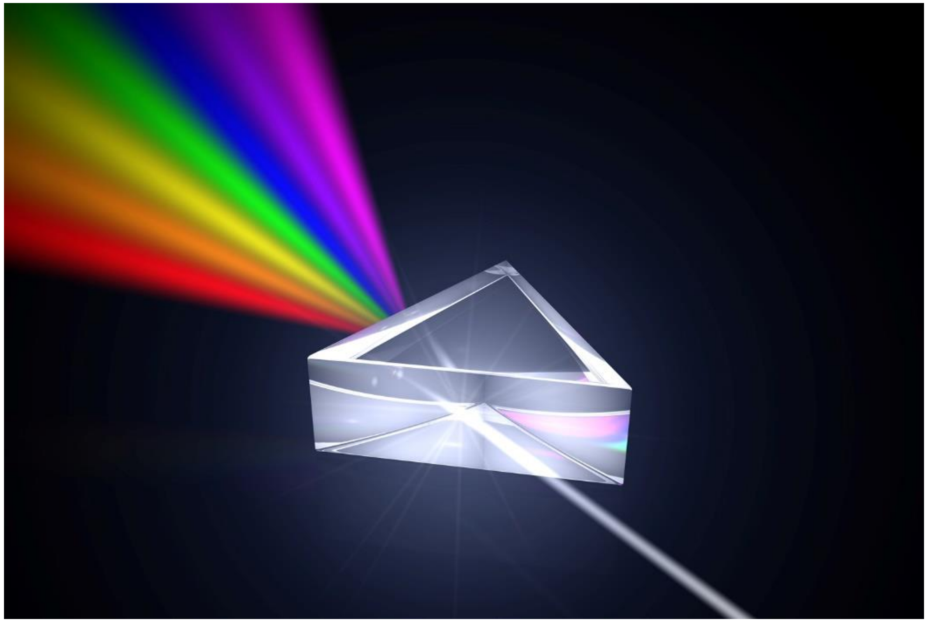


Spectrometers: main elements

- **Entrance aperture:** The image of a target is focused onto the slit. The slit is in the focal plane, and usually has an adjustable width w. The slit width must be matched to either the seeing conditions or the diffraction disk depending on the design and application. A narrower slit improves resolution $\sim 2 - 10\times$.
- **Collimator:** makes the rays parallel
- **Disperser** disperses the light into colours: grating or prism, usually on rotating stage so can adjust central wavelength.
- **Camera:** to re-focus parallel output beam from disperser onto focal plane of detector (CCD)

Disperser: Grating vs Prism





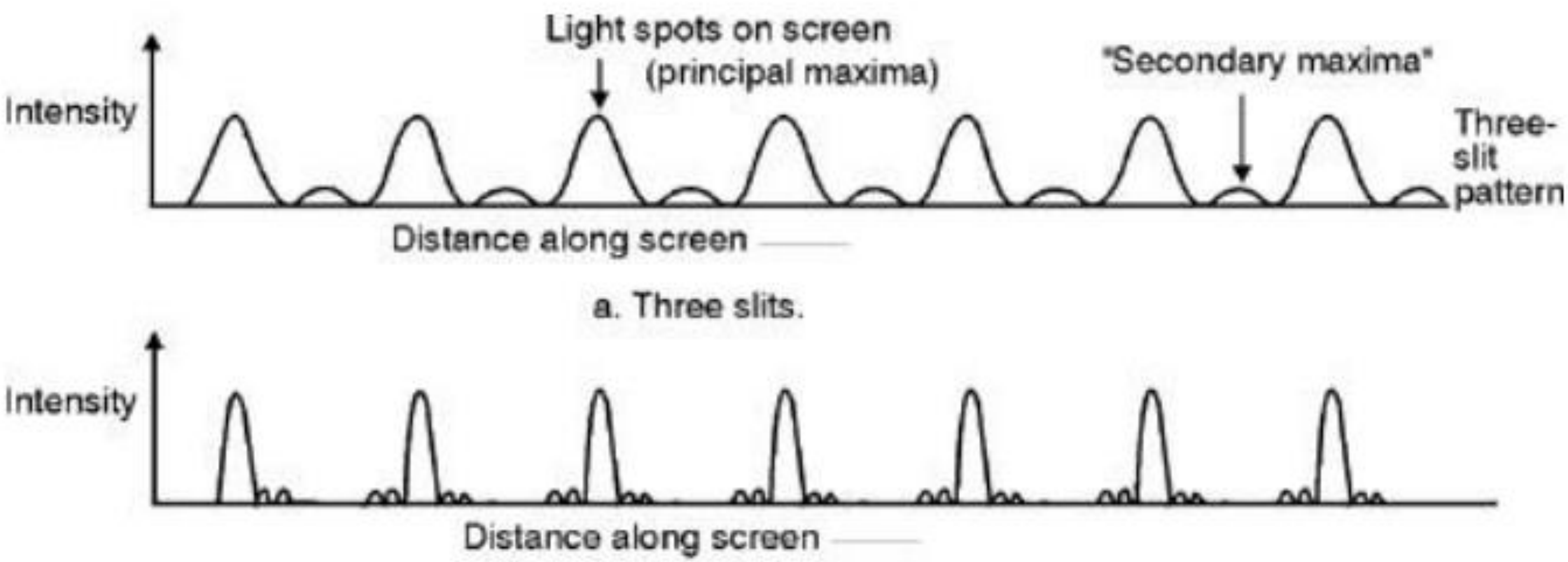
Resolution of a prism is low compared to what is possible with a grating, therefore **grating is usually the primary dispersive element in a modern spectrograph.**

Diffraction Grating

- A diffraction grating is a set of multiple, identical slits (transmitting or reflecting) separated by a distance comparable to the wavelength of light.
- Each slit can be considered as radiating secondary waves (Huygens' secondary wavelets).
- The amplitude at any point on the image side of the slit can be calculated by summing the amplitude contributed by each set of secondary wavelets.

Diffraction Grating

- The monochromatic multi-slit pattern for 3 slits and a large number of slits. Each peak corresponds to a particular order. The addition of slits **increases the sharpness** and brightness of the peaks **but leaves the locations** of the orders unchanged.



a. Three slits.

b. Many slits.

Diffraction Grating

- Principal maxima are given by the general grating equation:

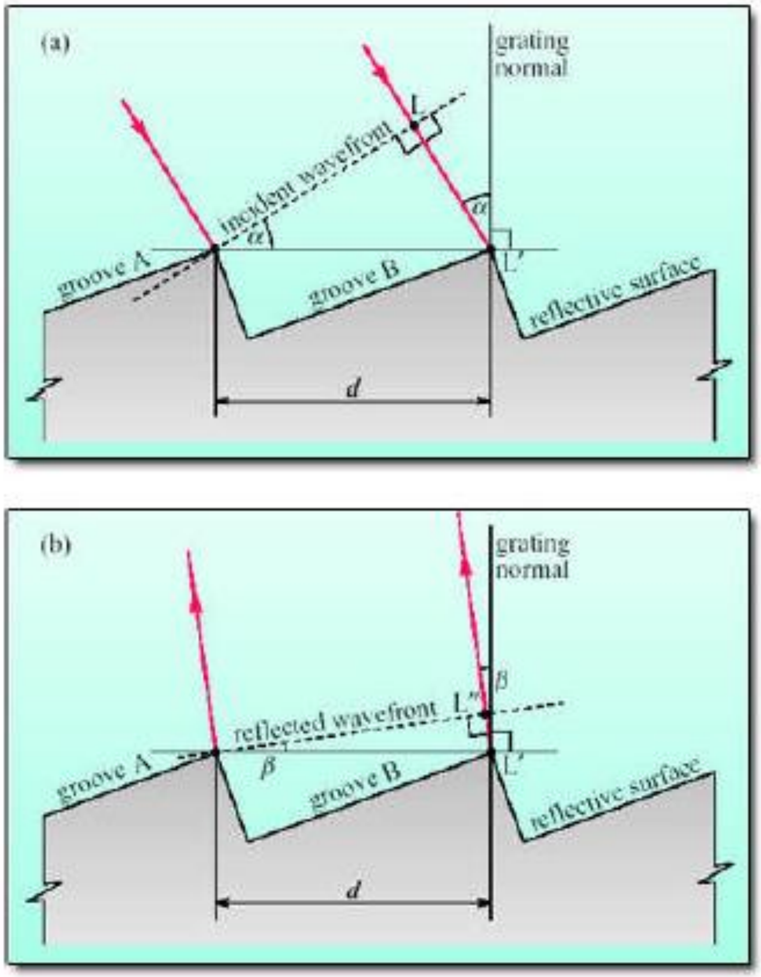
  $$n\,\lambda = d\,(\sin\alpha + \sin\beta)$$

  n is an integer representing the order in which the grating is being used. n is called the order of diffraction.

  d – the groove spacing.

  α – is the angle of incidence

  β – is the angle of diffraction



Resolving power & Spectral resolution

- Spectral resolution for order n is determined by the wavelength shift needed to place the diffraction pattern maximum for λ + δλ on the first minimum in the pattern for λ. The **resolving power** is

$$R = \frac{\lambda}{\delta\lambda} = nN$$

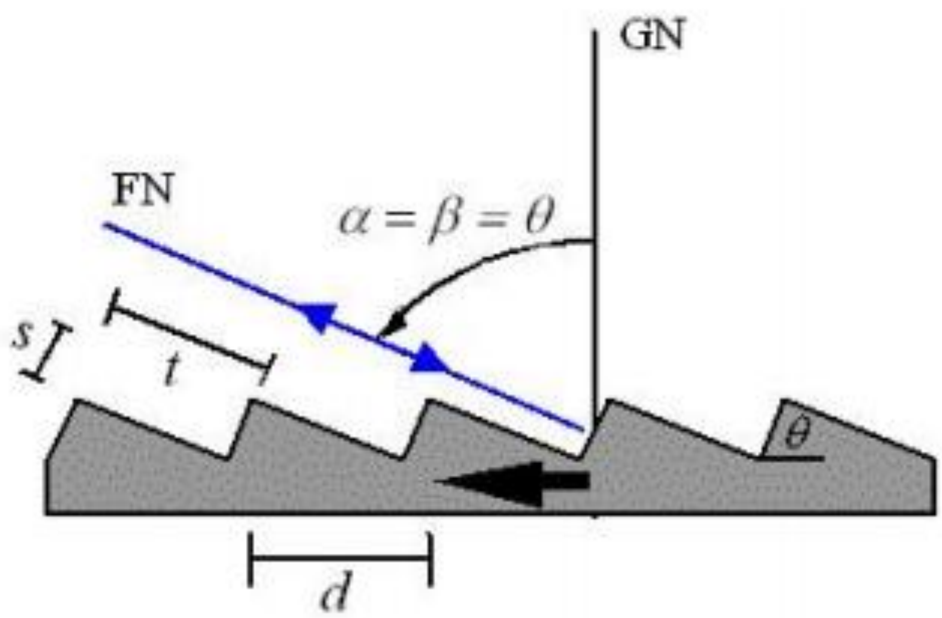
  it depends both on the order *n* and on the total number *N* of slits illuminated on the grating.
- Astronomers often use the word "dispersion" to refer to dλ/dx in the spectrograph focal plane, usually quoted in Å per mm. It is inversely related to the resolving power, so lower values correspond to higher resolving power.

Which resolving power to use for your observations?

- Always „the larger the better“ is not the answer
- High resolution needs a lot of photons, so to get any signal one needs a bright source and/or a large telescope
- Also, in some cases there is no need for high resolution. If the process you want to study produces velocities of 1000 km/s, there is not much point studying it with resolution of 1 km/s
- Still, with high resolution you might discover surprising things about your object

Diffraction Grating: Resolution

- "Echelle" gratings reach very high resolutions by operating at large $n \sim 50 - 100$ and angle of incidence $\alpha \sim 90^\circ$. Yield $R > 10^5$.



Order overlap

- Red light of a given order is spatially coincident with blue light from a higher order. Wavelength λ_m in order m is superposed on light from wavelength λ_n in order n if

$$\lambda_m = \frac{n\lambda_n}{m}$$

For instance, λ_1 = 10000Å, λ_2 = 5000Å, and λ_3 = 3330Å are coincident.

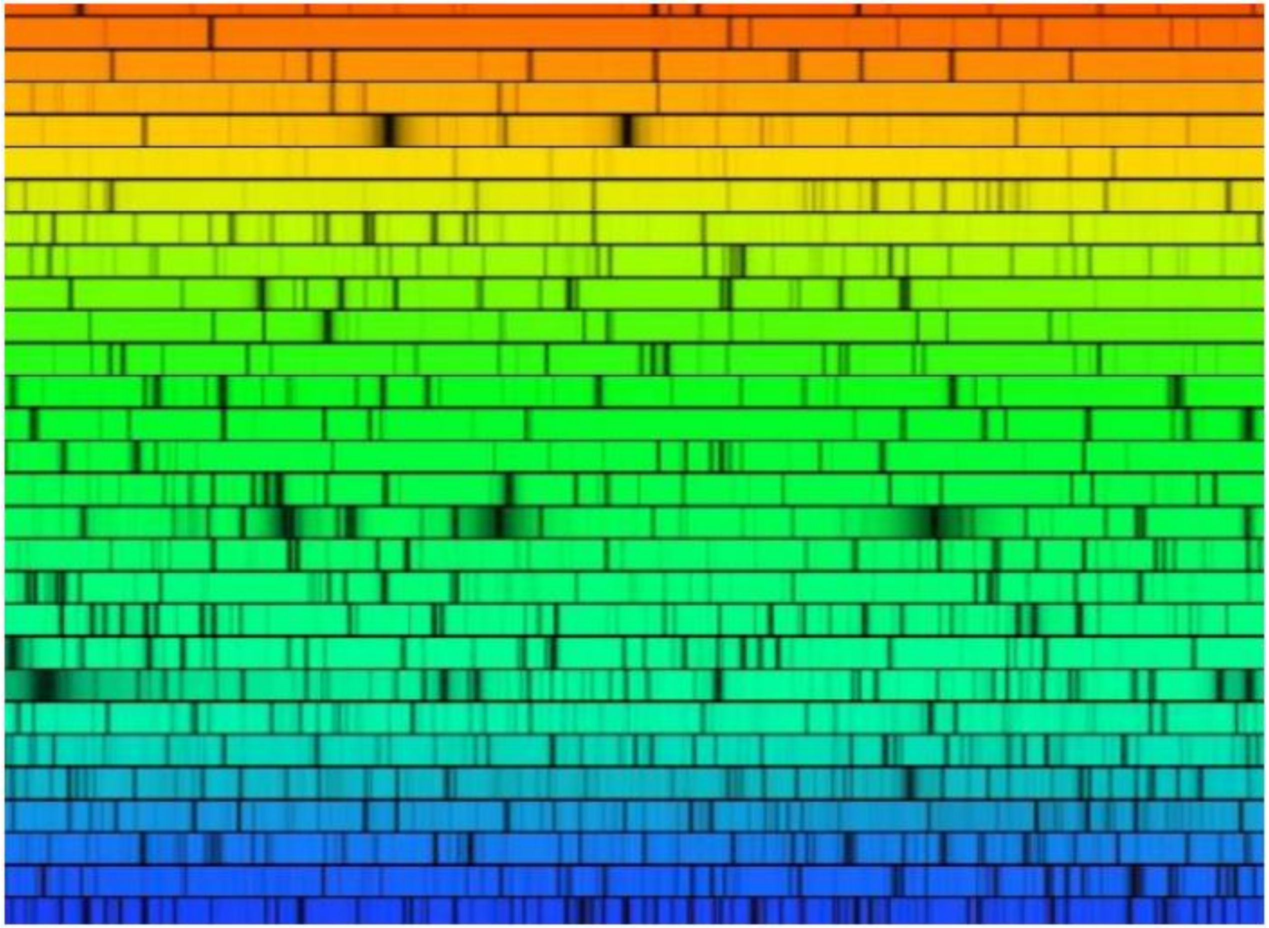
<u>Solution</u>: Use "order separating" filters to block out the unwanted orders,
(through this becomes difficult for large n).

Echelle gratings

- Order overlap is much worse, because adjacent orders differ in wavelength by small amounts (e.g. Order 6 @ 500nm is coincident with order 5 @ 600nm, order 7 @ 429nm, order 8 @ 375nm etc)
- Must separate these orders by cross-dispersion, usually dispersing with a prism at right angles to the grating dispersion.
- Echelle spectrum consists of a number of spectral orders arranged side by side on the detector.
- Echelles can only be used for point sources (stars and quasars) or for small objects, otherwise the light from different orders still overlaps.

Echelle gratings

High resolution, optical band solar spectrum



Transmission gratings and grisms

- A very popular way to convert a camera into a spectrograph is to deposit a transmission grating on the hypotenuse of a right-angled prism and use the deviation of the prism to bring the first order of diffraction on axis. Such a device is called a “grism".
- The advantage of a grism is that it can be placed in a filter wheel and treated like another filter.

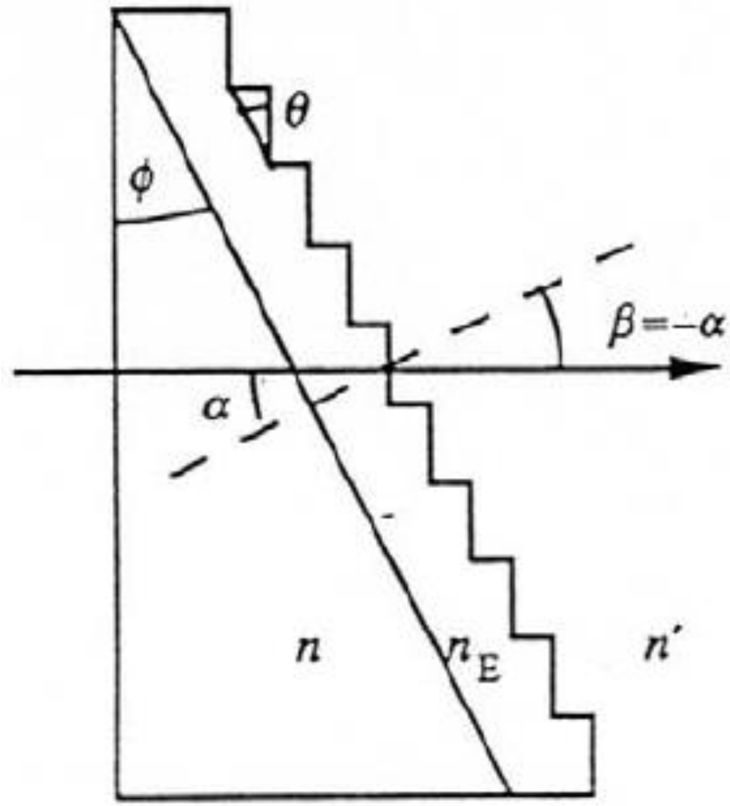
Grisms

- The basic relationships required to design a grism are

$$m\,\lambda_c T = (n-1)\sin\varphi$$

$$R = \frac{EFL}{2\,dpix}(n-1)\tan\varphi$$

where λ_c is the central wavelength, T(=1/d) is the number of lines per millimeter of the grating; n is the refractive index of the prism material; φ is the prism apex angle; EFL is the effective focal length of the camera system and d_{pix} is the pixel size. Resolving powers (two pixels) of R ~ 500 – 2000 are practical.



ALFOSC

- UV-optical imaging, low resolution spectroscopy and polarimetry
- 2048x2048 CCD (0.19”/pixel)
- 6.4’x6.4’ field of view (FOV)
- Large selection of broad, intermediate and narrow band filters
- Several grisms:
  - R~200-10,000 (typically 1000)
  - Velocity resolution 30-1500km/s
- Multi Object Spectroscopy with masks
- Imaging polarimetry and spectropolarimetry
- Spectroscopy of objects brighter than R~20
- Imaging of objects brighter than R~23.5

Practical spectroscopy

Practical spectroscopy

- The purposes of spectroscopy are:
  - To measure accurate wavelengths of emission and absorption lines.
  - To measure the relative strengths of emission lines.
  - To measure equivalent widths of absorption lines.
  - To measure the spectral energy distribution of the continuum radiation.

Practical spectroscopy

- Science goals must come first:
  - What are the resolution and S/N requirements?
  - Is there a restriction on exposure time?
  - Decide on the best compromise between these constraints, you will soon enough run out of photons.
- Identify a slit-width/disperser combination that provides the required dispersion and sampling.
  - Seeing or slit-width limited?
- Work out calibrations required
  - Always try to take cal data through the same/similar lightpath.

Slit-filling effects

- A slit-limited setup ensures that the slit is always illuminated uniformly [provided the object is centered]
- A partially illuminated slit (because image quality is better than the slit-width) may introduce shifts in the projected spectrum as different areas of the slit are illuminated as a function of time
- This will lead to shifts in both the spatial and dispersion direction of the spectrum when comparing to calibration data that are obtained with a fully illuminated slit
  Not good if you are after accurate radial velocities!

Atmospheric dispersion

- Differential atmospheric refraction will deflect a source by an amount that is dependent on wavelength
  - [the index of refraction is a function of wavelength]
- A point source position on the sky is dependent on wavelength!
- The displacement is towards the zenith and larger for shorter wavelengths
- This obviously affects acquisition and slit-angle strategies when obtaining spectroscopy

Atmospheric dispersion

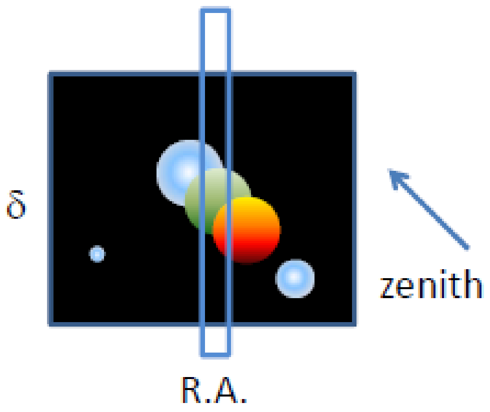
- Index of refraction: n(λ,T,p,f)
  - wavelength, temperature, pressure, water vapour
- Angle displacement: $\Delta R = R(\lambda_1) - R(\lambda_2) \propto \Delta n(\Delta\lambda) \tan z$

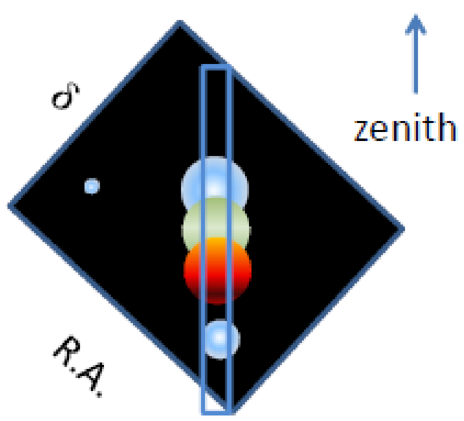
  zenith angle (airmass)
- Some example shifts (") relative to image at 5000Å:

airmass	3000Å	4000Å	6000Å	10000Å
1.00	0.00	0.00	0.00	0.00
1.25	1.59	0.48	-0.25	-0.61
2.00	3.67	1.10	-0.58	-1.40

Atmospheric dispersion

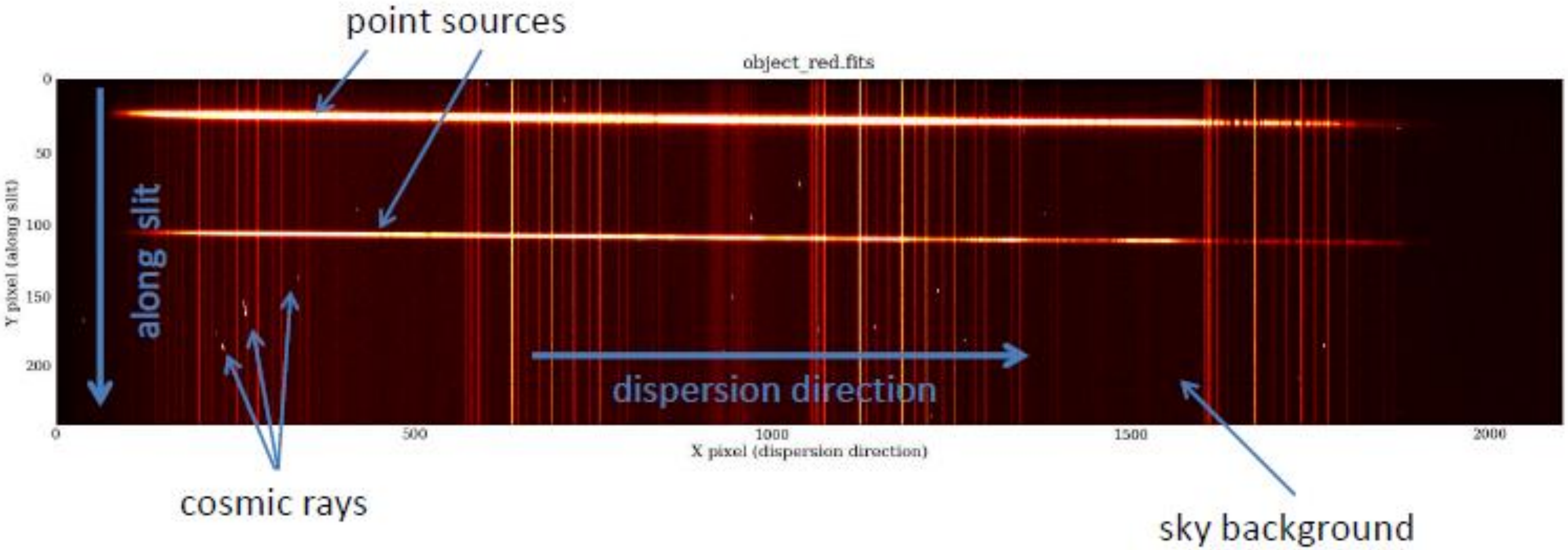
- Make sure you acquire the target at a wavelength relevant for your spectral range
- Differential refraction will mean differential slit-losses: can only centre object at one λ
- If the slit is vertical (relative to horizon/ zenith line), differential refraction will occur purely along the slit
- This means that the slit P.A. (sky angle) must change with time. The vertical P.A.is the *parallactic* angle



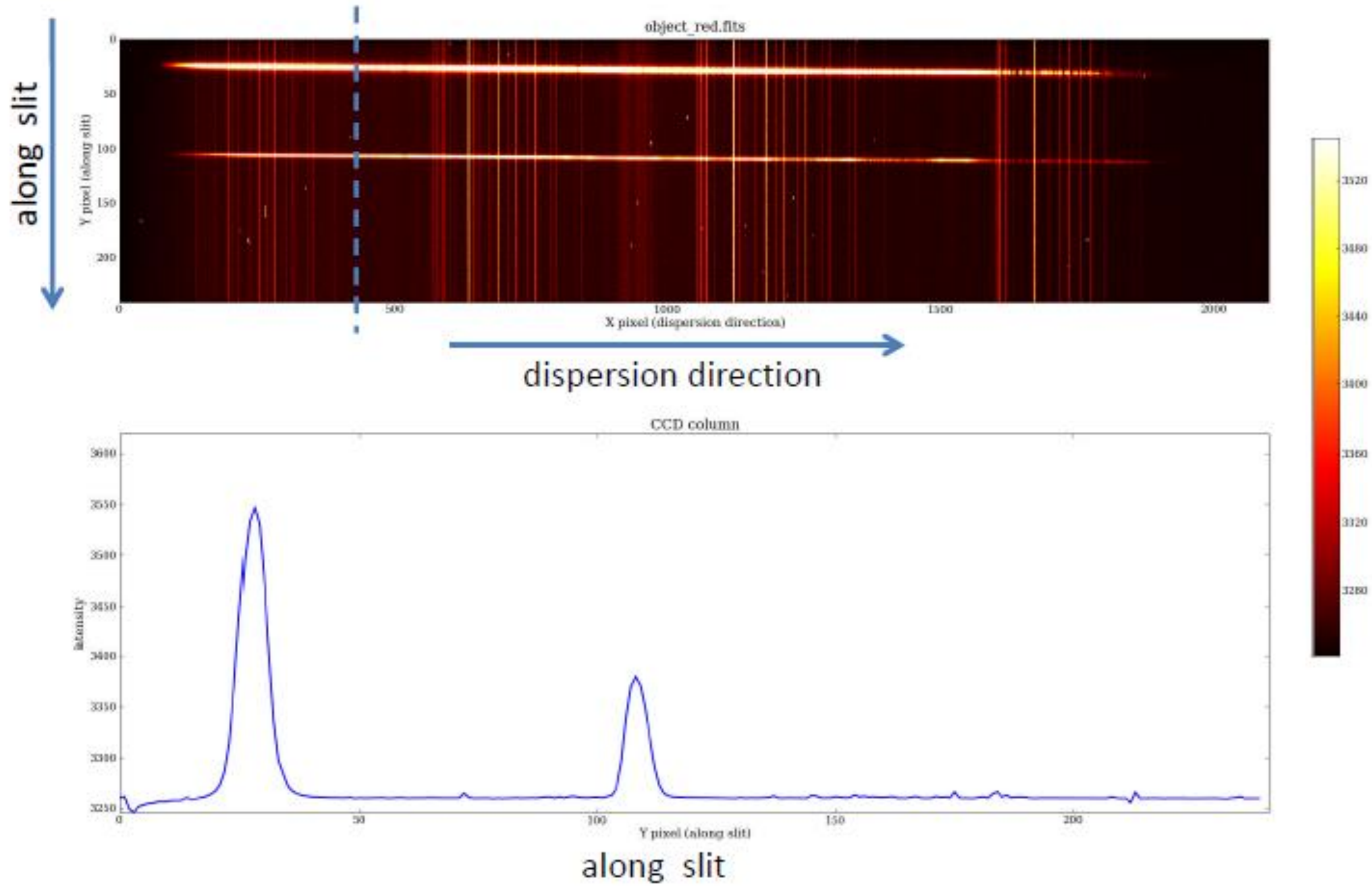


Calibration

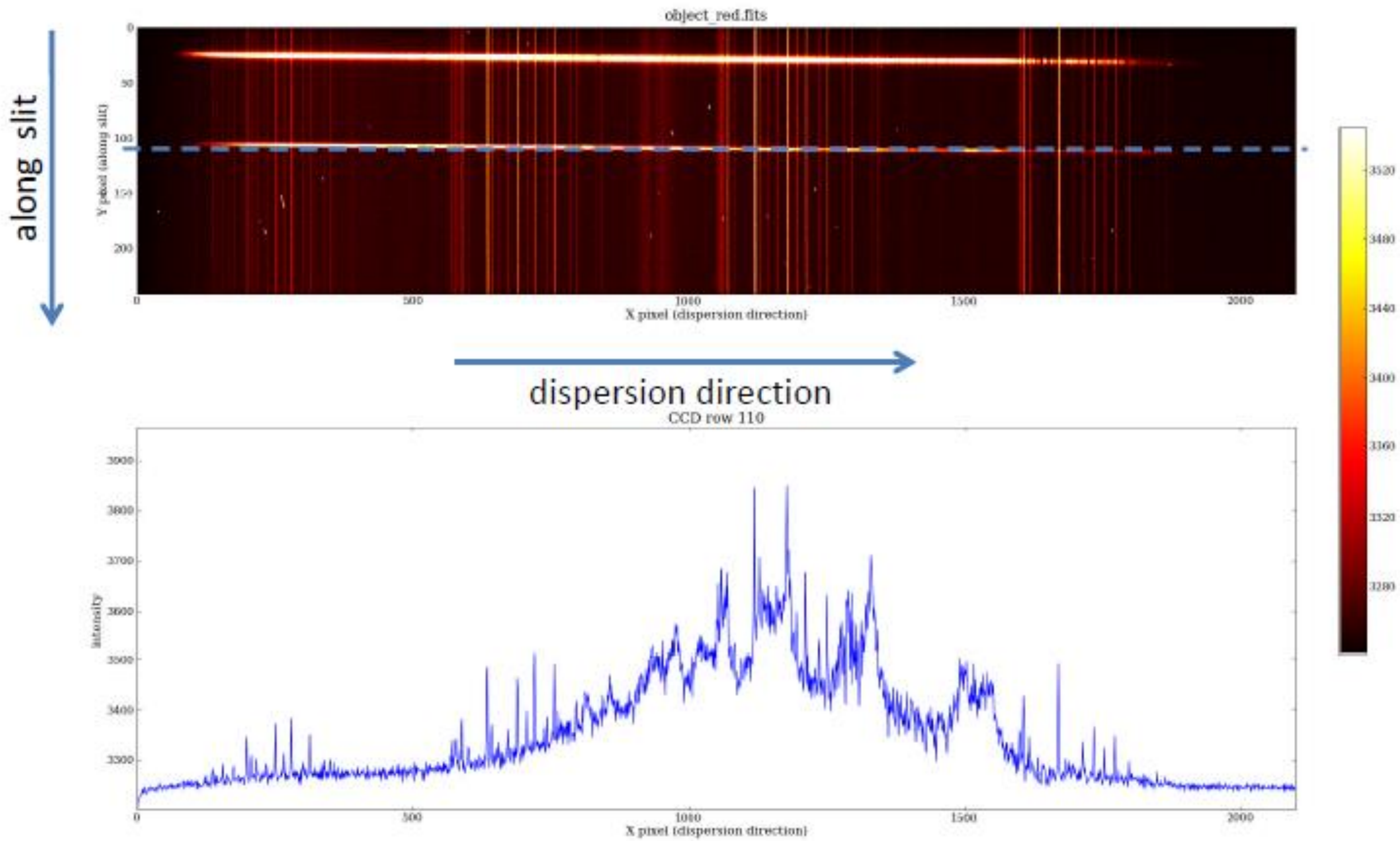
A long slit spectrum



A long slit spectrum: spatial slice



A long slit spectrum: spectral slice



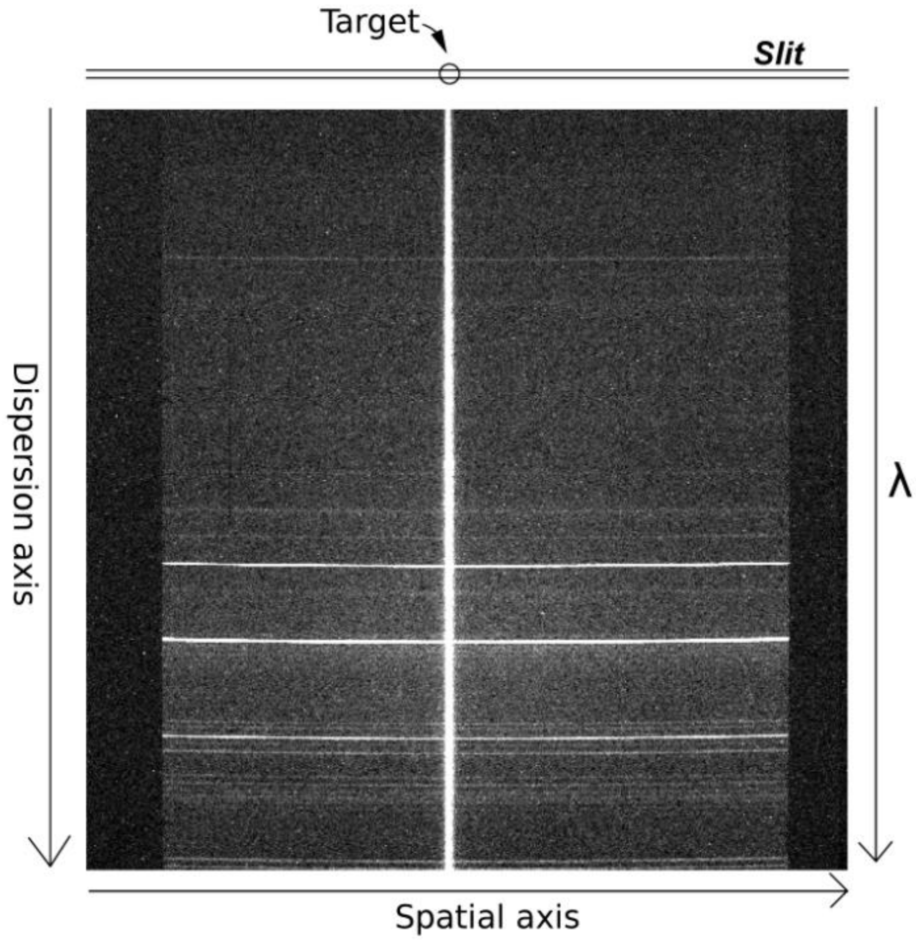
Calibrations

- The first stage of calibration is to calibrate the detector, and the steps in doing this are exactly the same as for photometric observations.
  - Subtract off the CCD bias signal, either as a constant value or as a frame.
  - Subtract off the dark current, either as a constant value or as a frame. As spectroscopic exposure times are longer than photometric exposure times, this step is now more often needed.
  - Divide by the flat field frame to correct for variations in the sensitivity of the detector.

Reducing spectra

- In addition to the science frames you will need:
  - Bias frames
  - A continuum lamp image (for flat-fielding)
  - A line lamp (so-called arc) frame (for wavelength calibration)
  - A standard star spectrum (for flux calibration)
- The continuum and line lamps are inside the instrument in a special calibration unit. They are obtained immediately before or after the science observation

An ALFOSC long slit spectrum

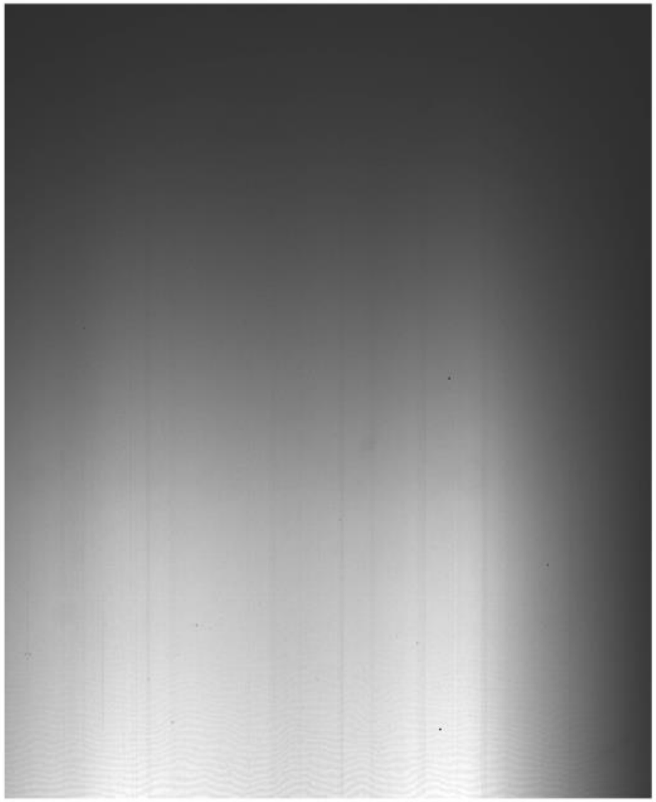


A simple rule:

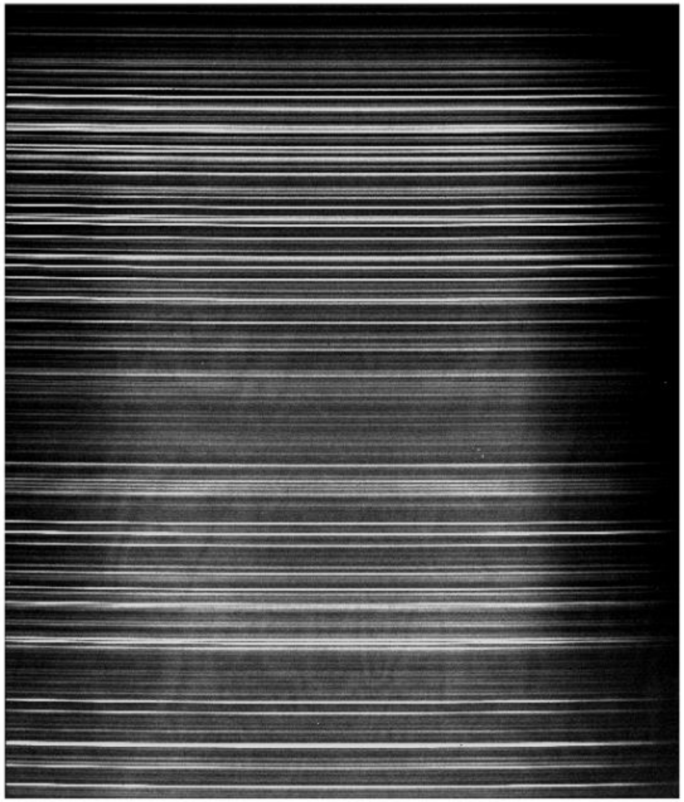
The spectrum on the CCD can be thought as the *image of the slit at different wavelengths*.

Calibrating spectra

Continuum lamp
(For flat-fielding)

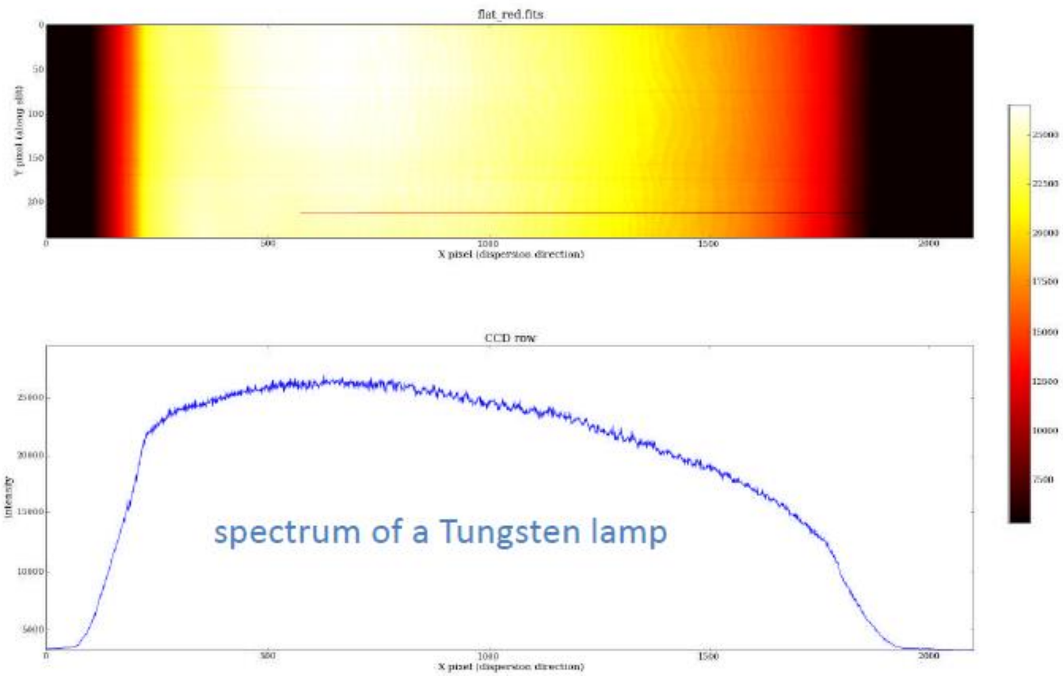


Line lamp
(For wavelength calibration)



Flat-fielding

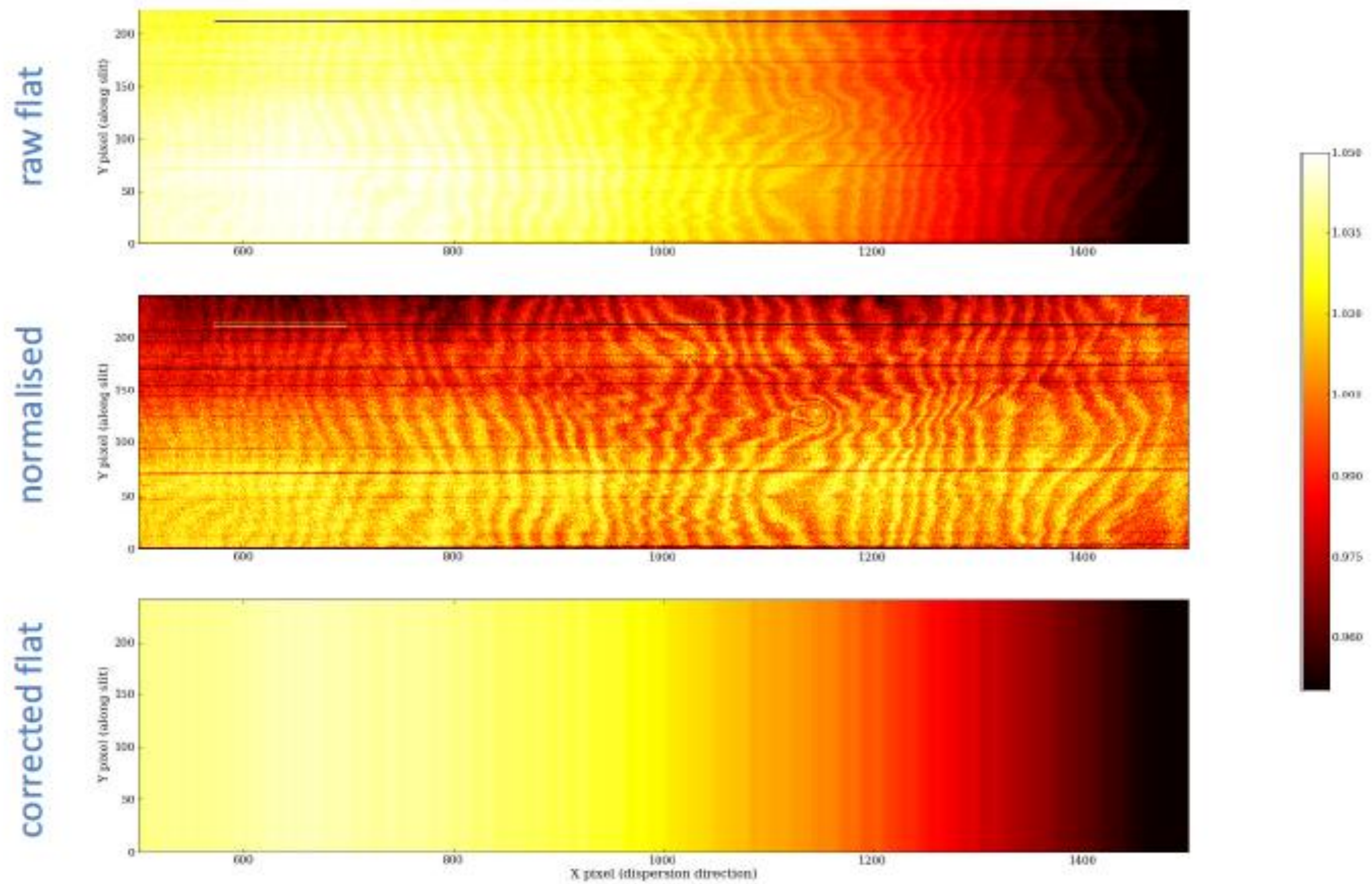
- Flat-fielding is probably one of the trickier steps
  - Uniform illumination along the slit
  - Uniform illumination along the dispersion direction
    - Need a light source with a smooth/simple spectrum



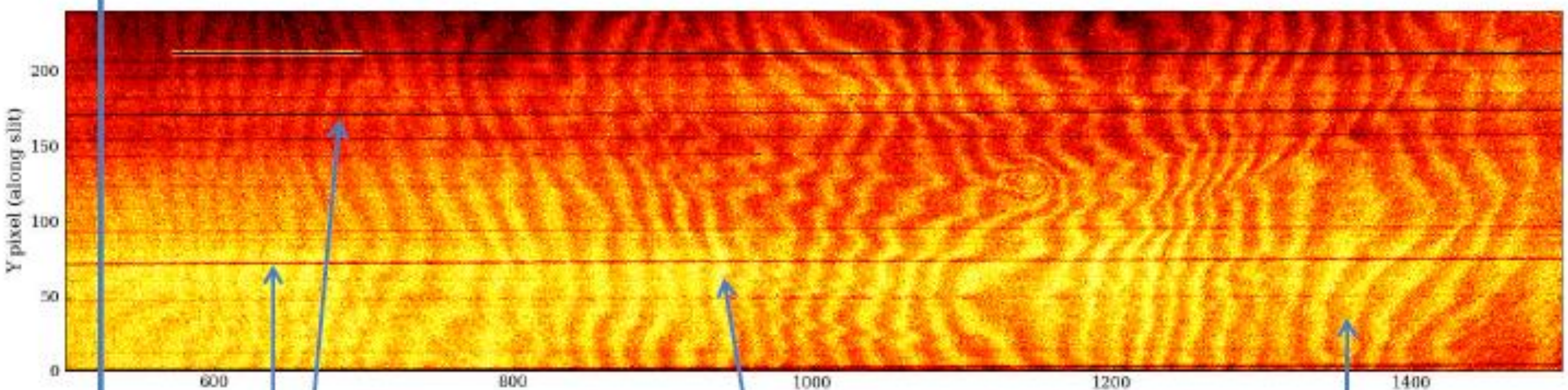
Flat-fielding

- The trick is to remove the spectrum of the calibration lamp and normalise the flatfield
  - Not always possible to distinguish between broad CCD sensitivity features and features in the lamp

Flat-fielding



Flat-fielding



crap on the slit

pixel-to-pixel sensitivity

fringes

Watch for gradients/structure along the slit, may need a twilight flat (useless in the spectral direction) to correct spatial profile

make sure slit width, grating angle, filters are all in place, replicating as much the light path to the science frames

Extracting the spectrum

signal = (source + background) – background@source

$$\mathbf{S}(\lambda) = \Sigma\, I(y,\lambda)\, p(y) - \Sigma\, I(y,\lambda)\, b(y)$$

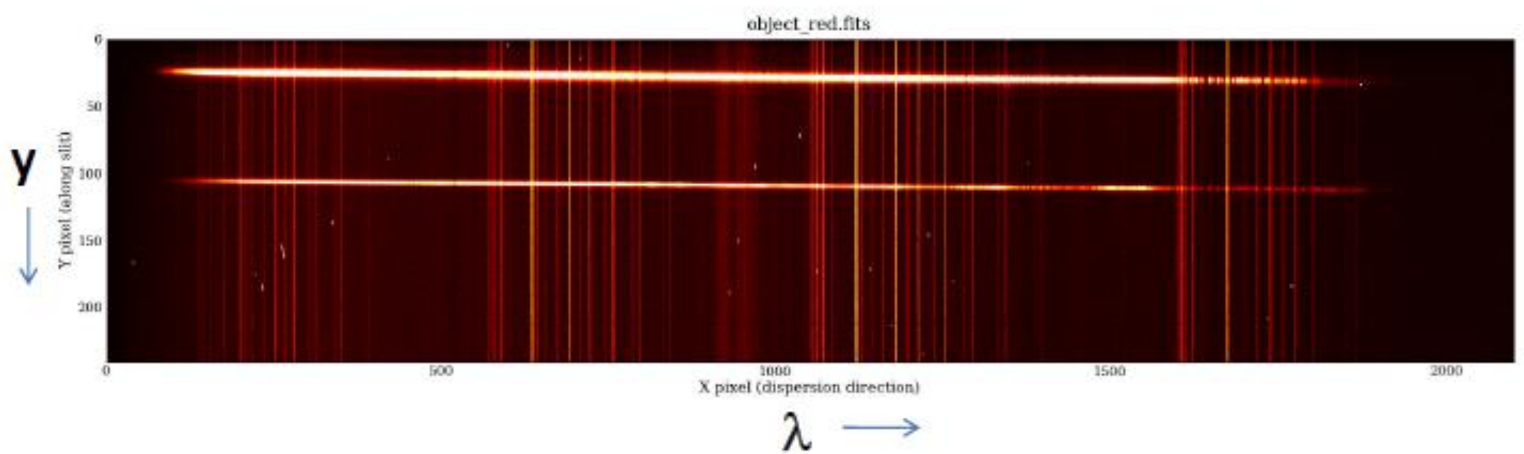
object profile weight

sky profile weight

$$D(\lambda) = f(x,y) \approx f(x)$$

relates λ to x,y

dispersion relation

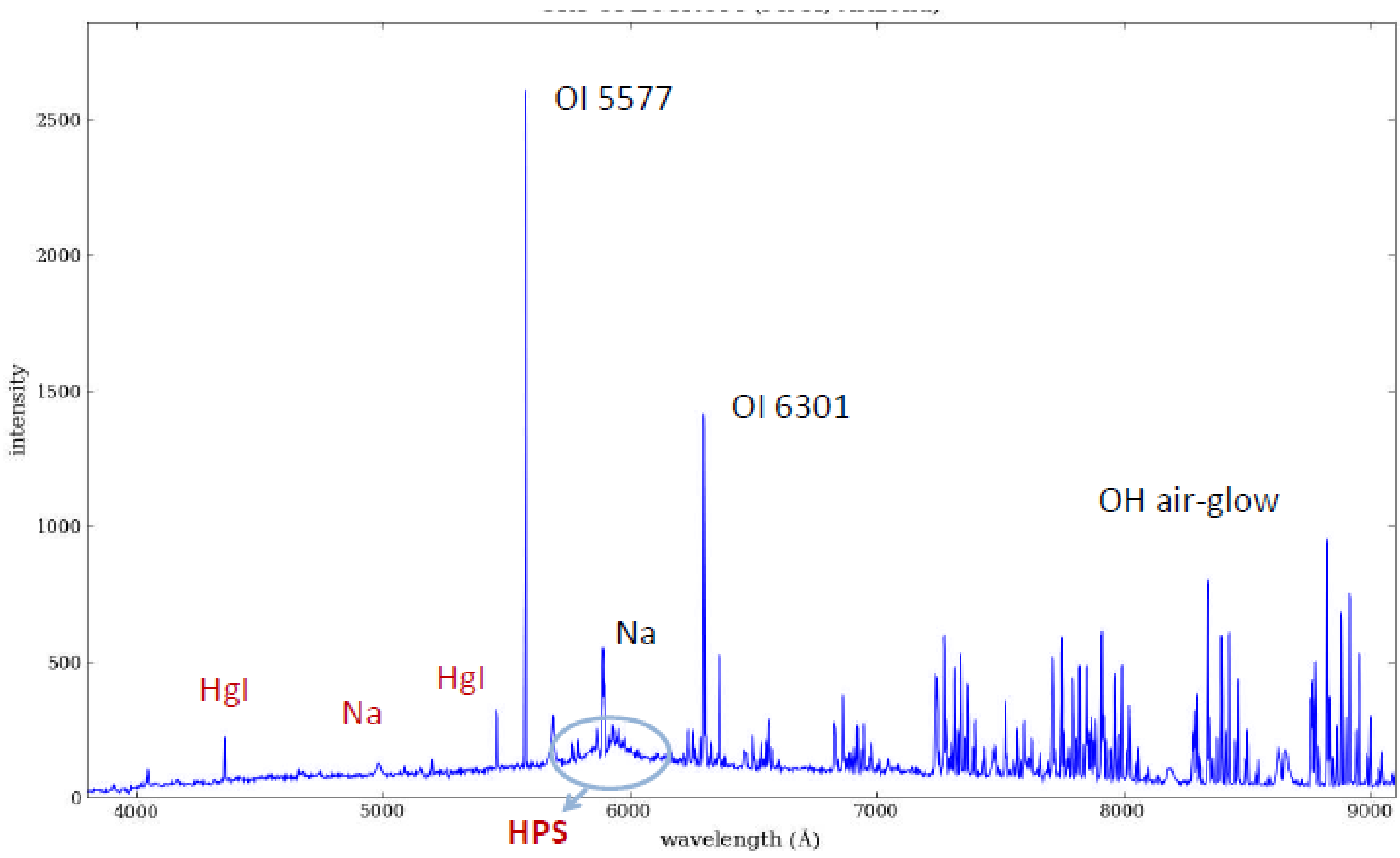


Sky background

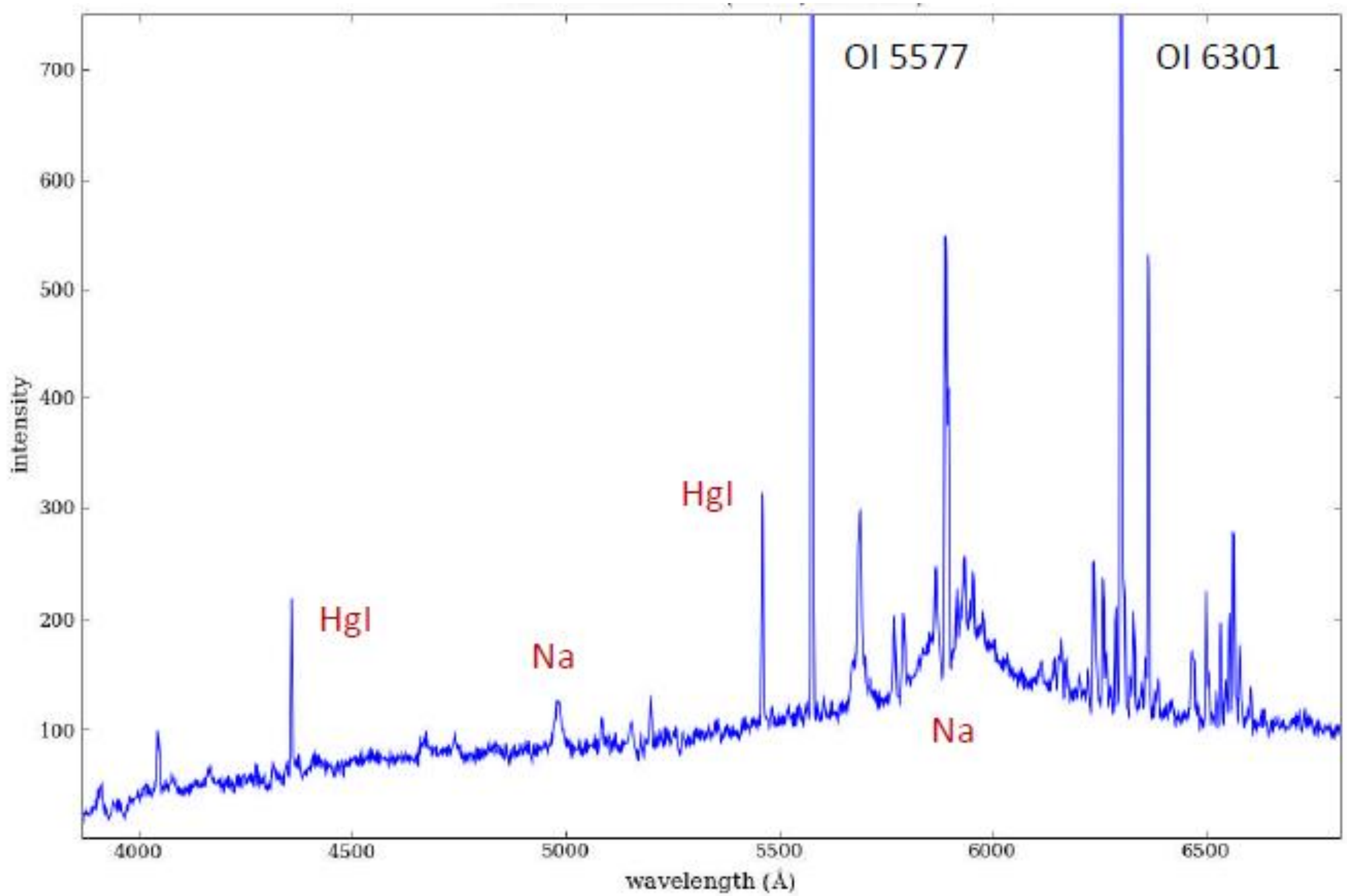
Background has contributions from many sources;

- Air glow ; strong discrete emission lines
- Zodiacal light ; $m_V \sim 22.-23.5$
- Sun/Moonlight
  - new moon : $m_V \sim 21.9$
  - full moon : $m_V \sim 19.9$
- Aurorae
- Light pollution
- Thermal emission from sky, telescope and buildings
- Non-resolved astronomical background

Sky background

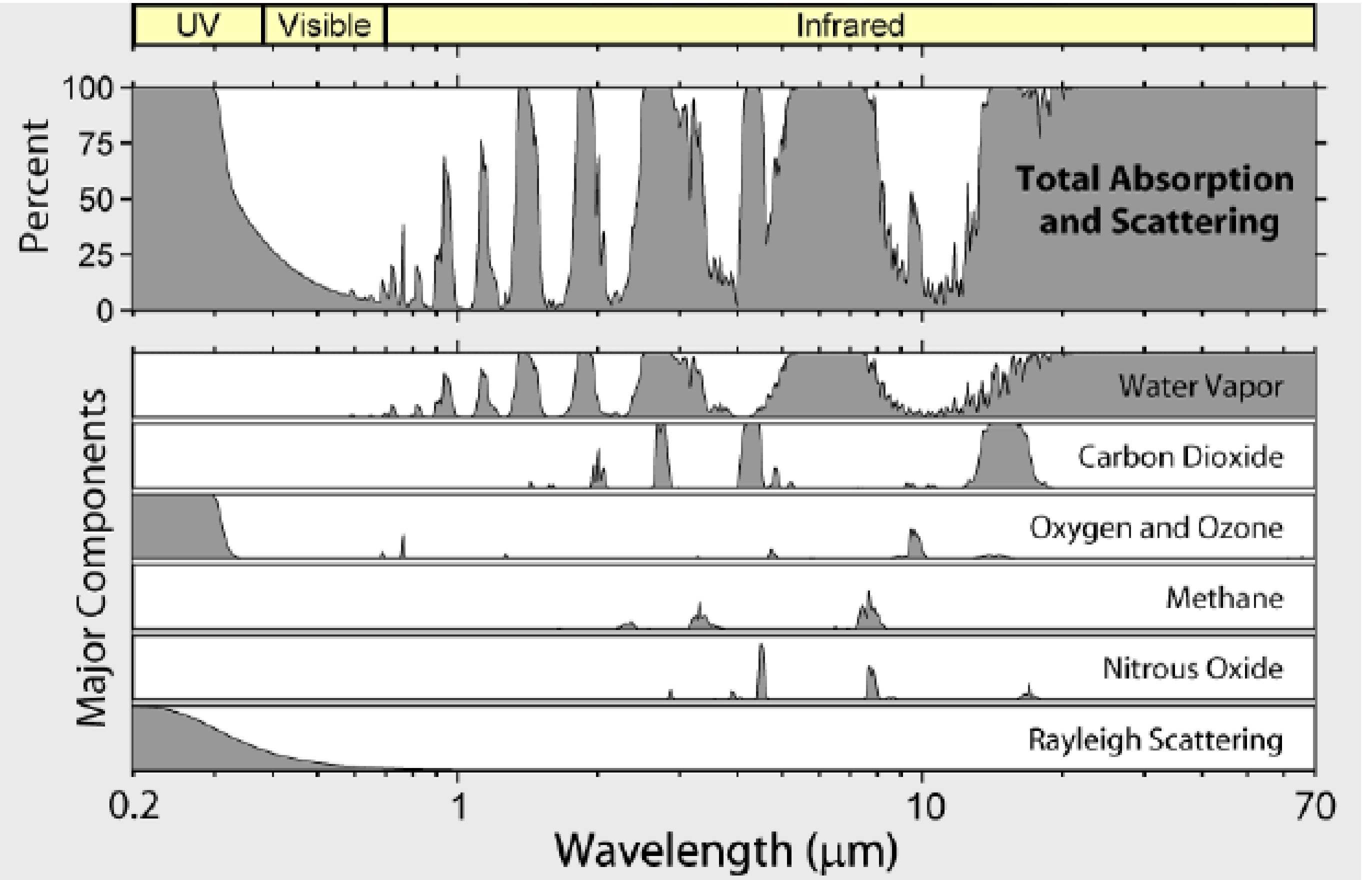


Sky background

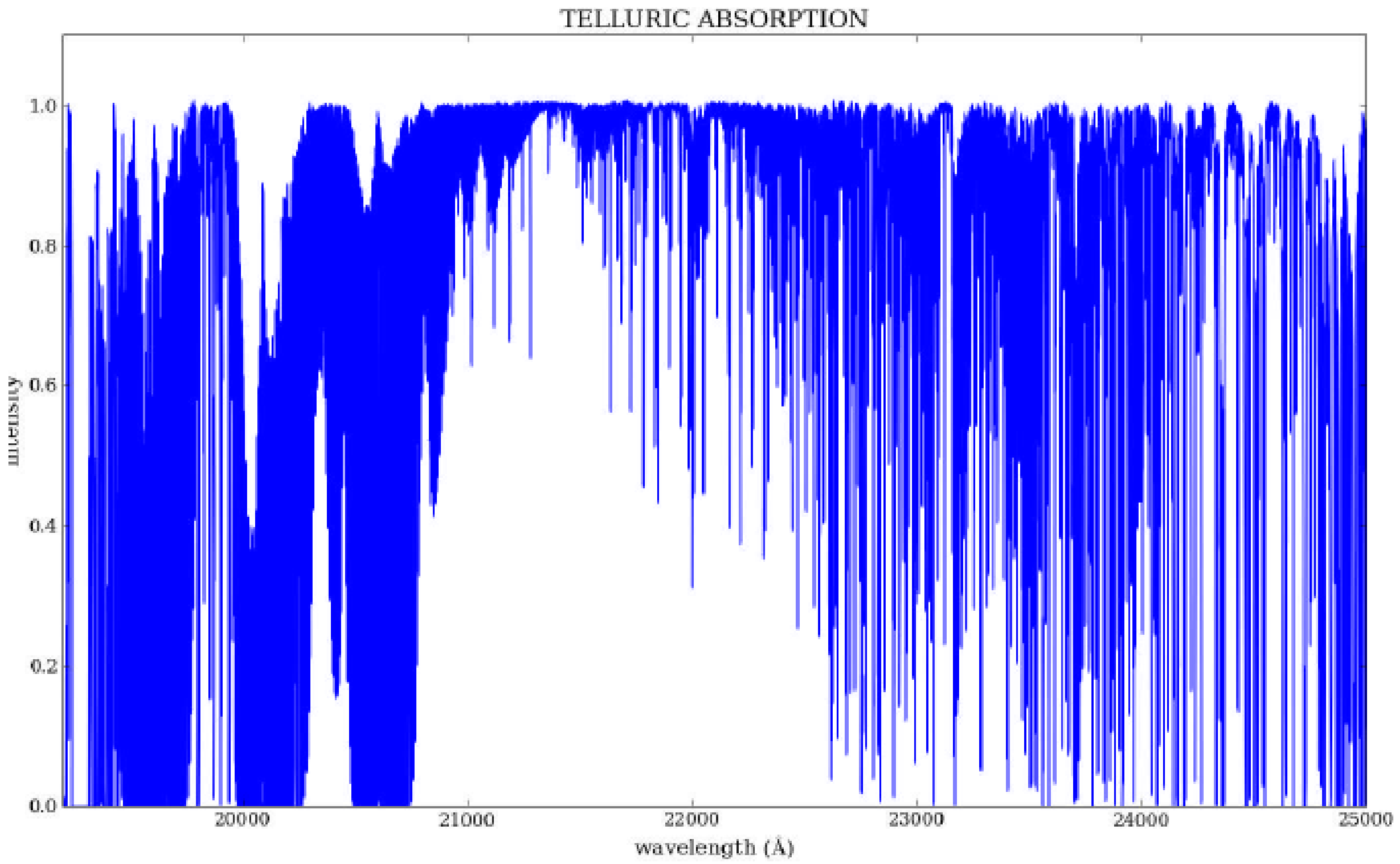


Atmospheric transmission

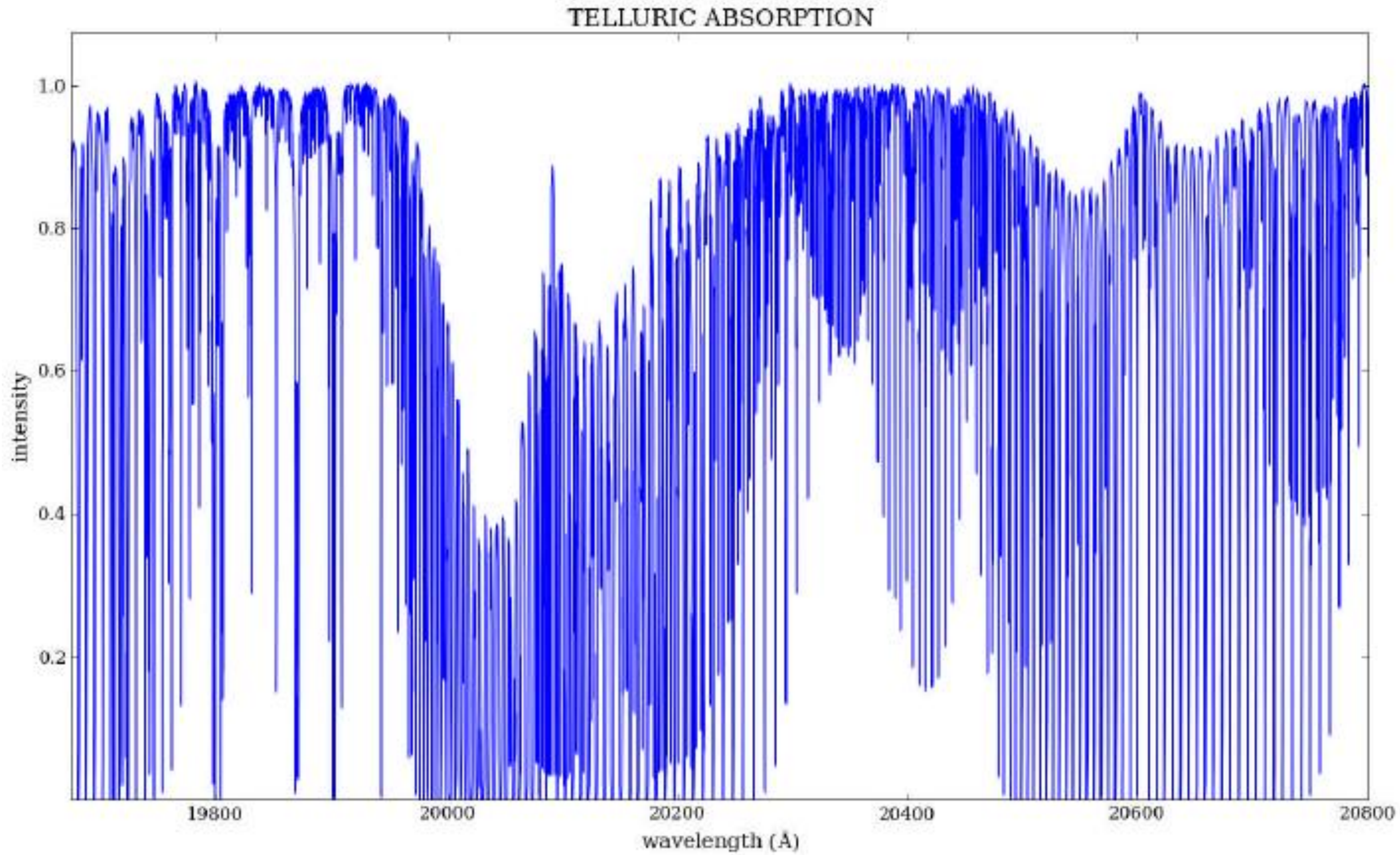
Atmospheric transmission is strongly dependent on wavelength



Telluric absorption



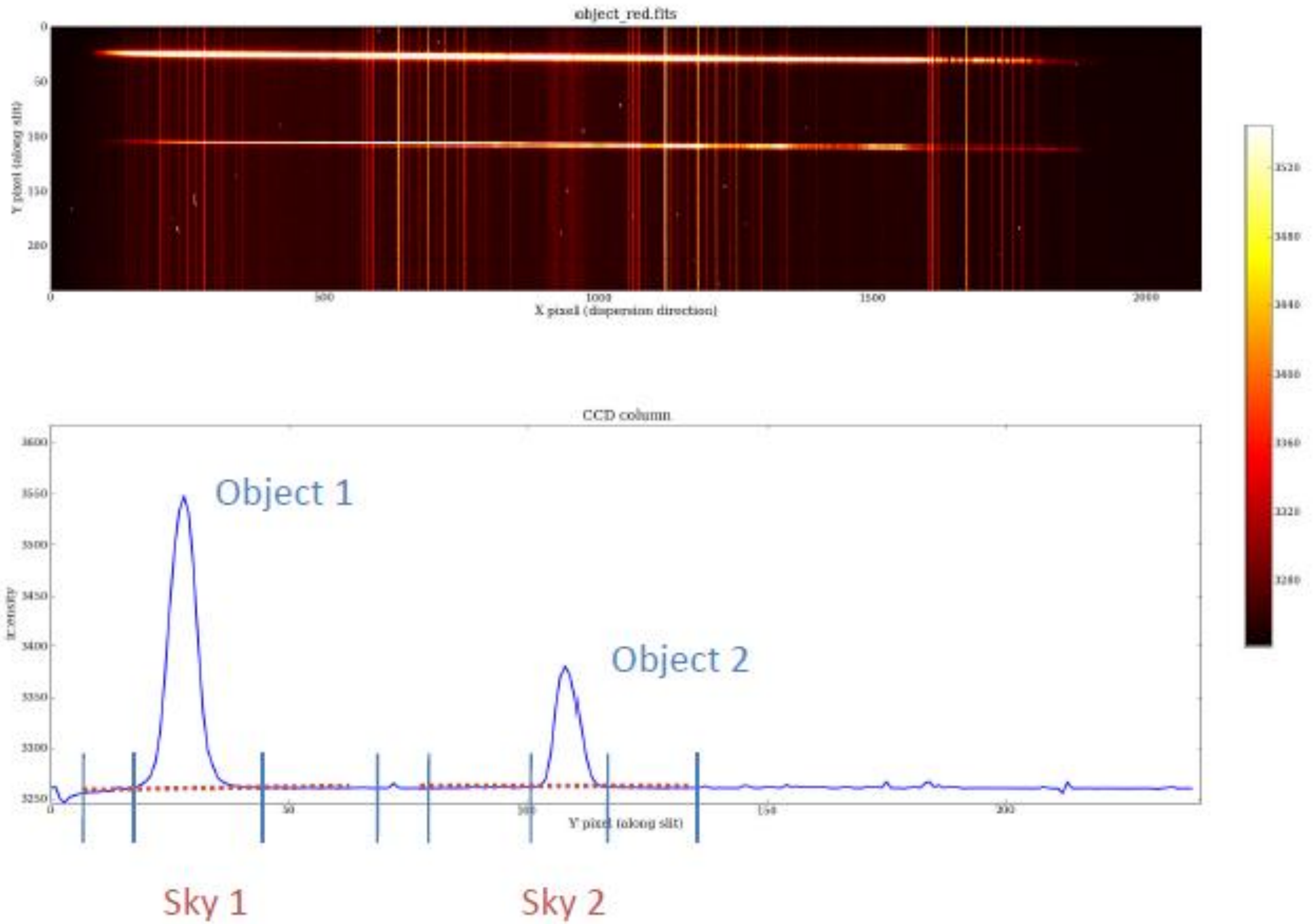
Telluric absorption



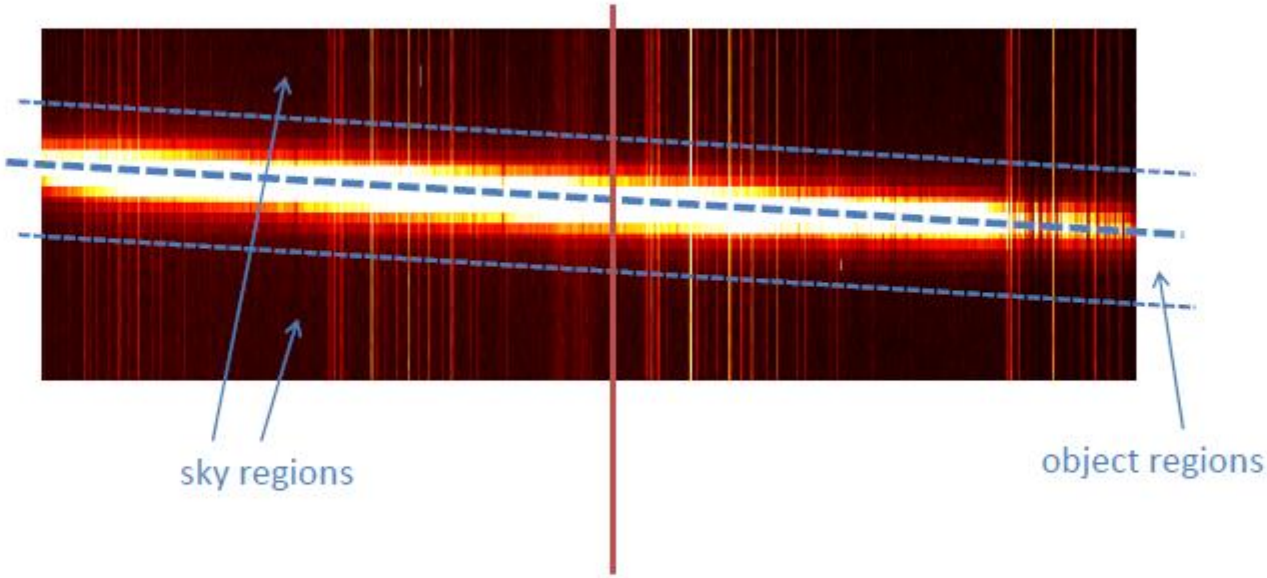
Summary: Background

- The background is a composite of many sources
- All of these are dependent on wavelength and their strength varies with time
- Some correlate with lunar cycle, airmass, solar activity cycle, etc, but many variations are erratic
- *Background subtraction needs to be done on a wavelength by wavelength basis* and ideally is measured simultaneously with the object exposure
- Some parts of the spectrum may be background dominated, others not *; error propagation*

Locating the object and sky

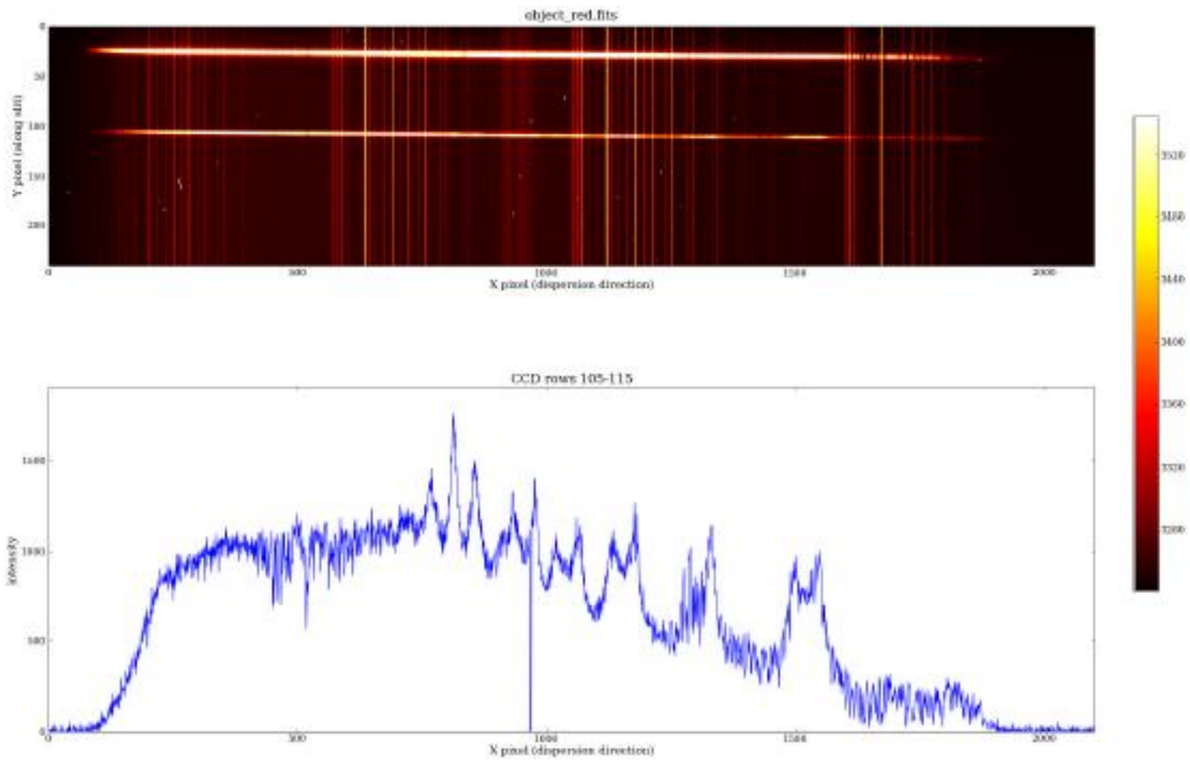


Tracing and skyfit



- Evaluate sky background at each wavelength by considering the sky pixels around the shifting object
  [if you are lucky, sky lines are well-aligned with the CCD columns]
- This gives you the *fitted* background value **at the location of the object**

Net signal: naive method



$$\mathbf{S}(\lambda) = \Sigma \; (I(y,\lambda) - sky(y,\lambda))$$

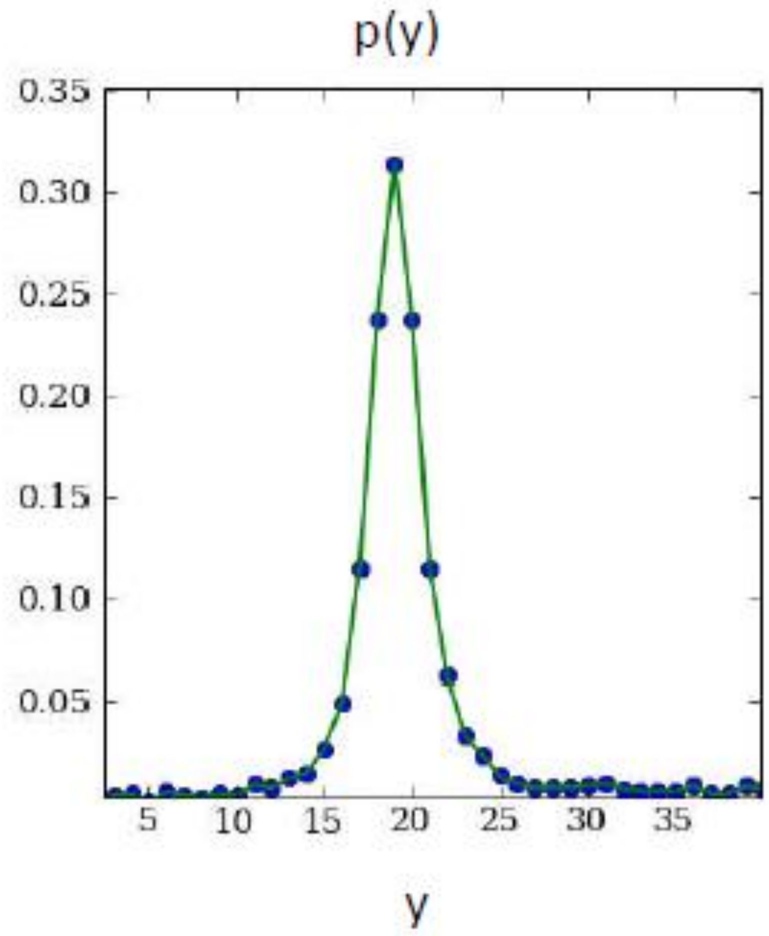
unweighted sum over object region

skyfit at each object pos

Net signal: optimal extraction

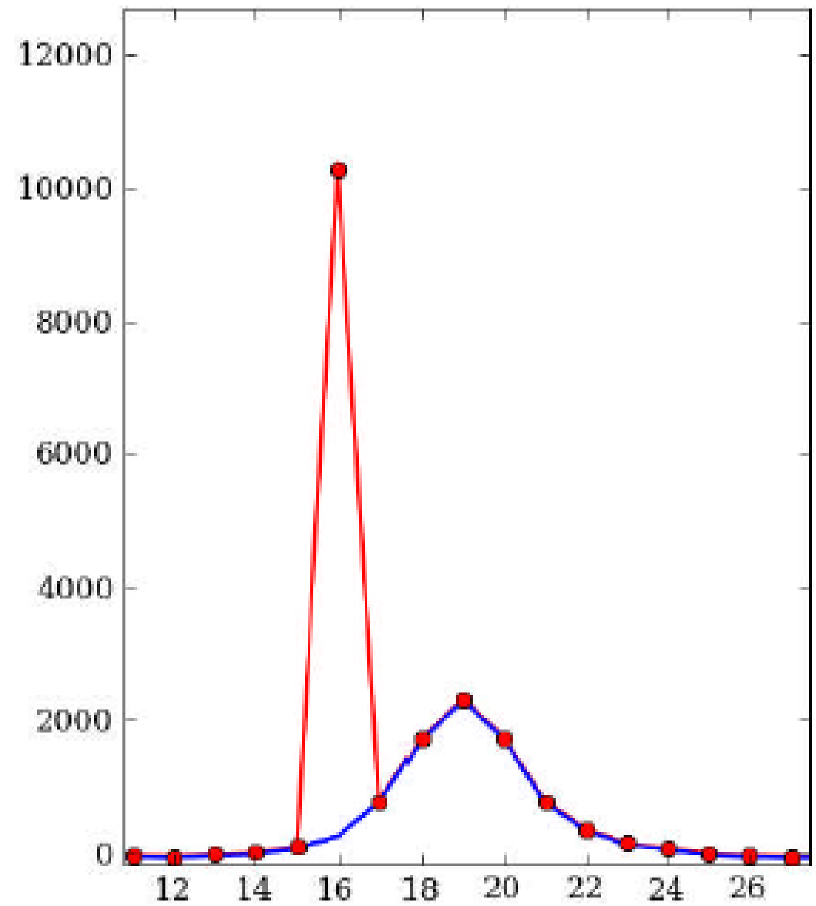
- Optimal sum across the object profile considers the fractional contribution of a given pixel to the total light at that wavelength and weighs its contribution
- Profile p(y) is measured from the 2D frame and normalised such that Σ p(y) = 1 when summed along the extraction region
- Optimal weights (minimising variance):

$$w(y) \propto p(y)/\sigma(y)^2$$



Net signal: optimal extraction

- Need to estimate $\sigma(y)$ reliably from readout noise and gain such that Poisson noise and background subtraction errors are properly propagated
- Not only provides the optimal sum with a significant S/N improvement in the extracted spectrum, but also allows the easy flagging of outlier pixels due to cosmic rays or CCD defect



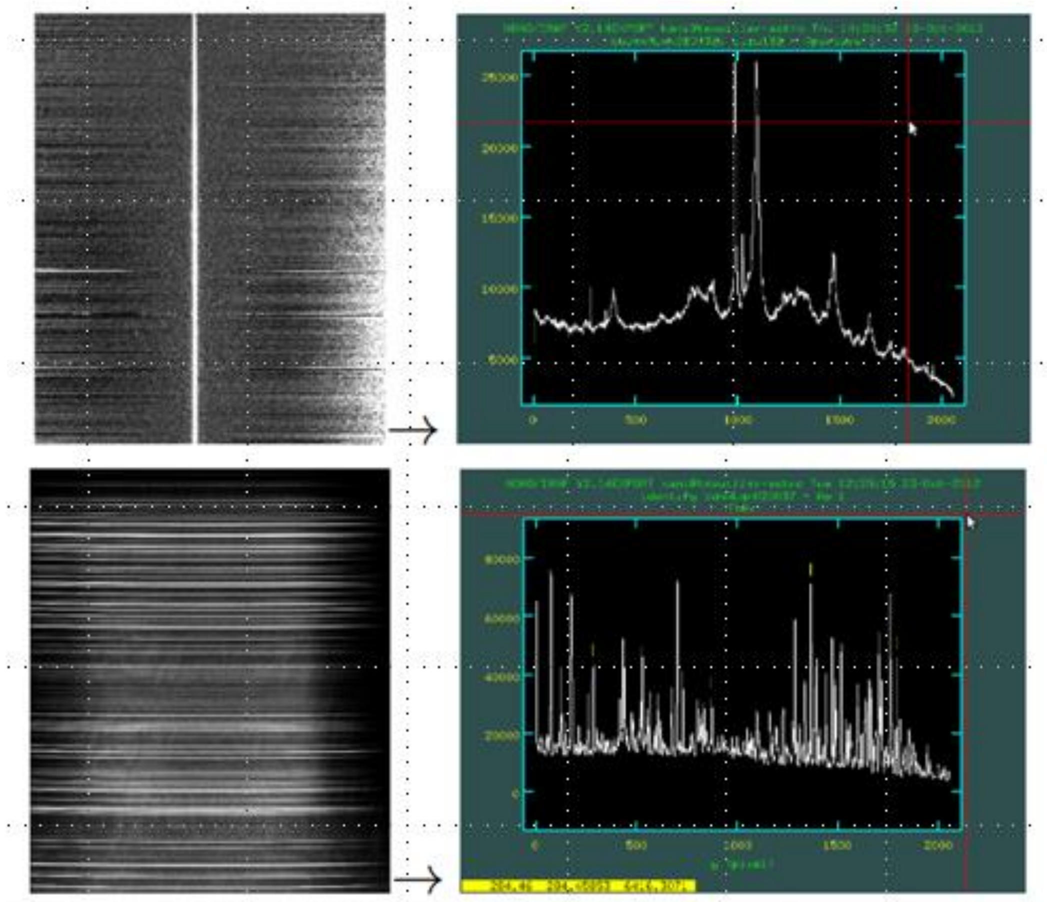
Wavelength calibration

- **Wavelength calibration** – a comparison spectrum usually of a hollow cathode discharge lamp, gives a series of emission lines of the gas in the lamp, plus the metal or metals that the cathode is made from.
- Typically the gas is a noble gas (helium, argon, neon etc.) and the metal is copper, iron or thorium.
- Using the laboratory determined wavelengths of these lines a functional fit of wavelength against position on the detector is made.
- In principal this is a two dimensional fit, although in practice the dispersion direction is usually accurately aligned with one of the principal axes of the detector (usually vertical on a CCD), so this reduces to a series of one dimensional fits, one per CCD column.

Wavelength calibration

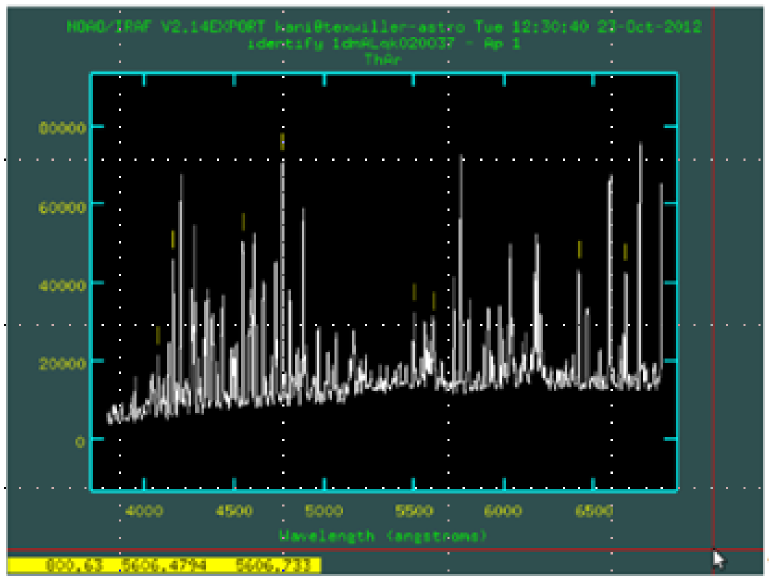
Extract the 1-d spectrum of the star

Extract the lamp (arc) spectrum



Wavelength calibration

- Determine wavelengths of arc-spectrum lines and the transformation equation from pixel coordinates to λ



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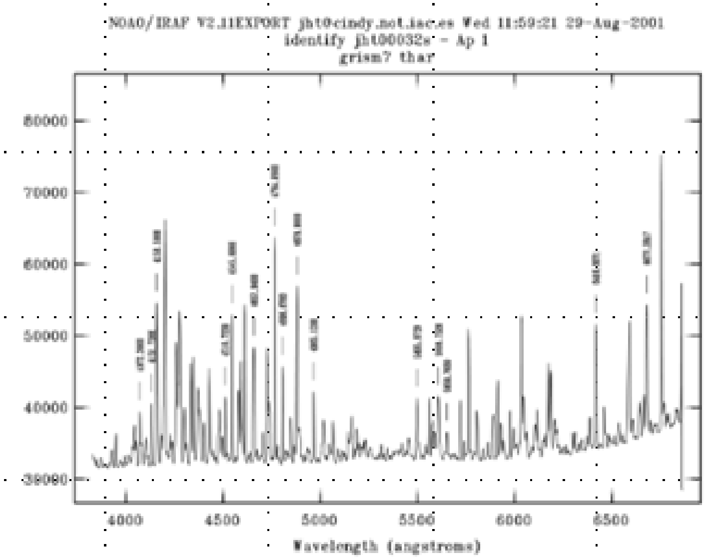
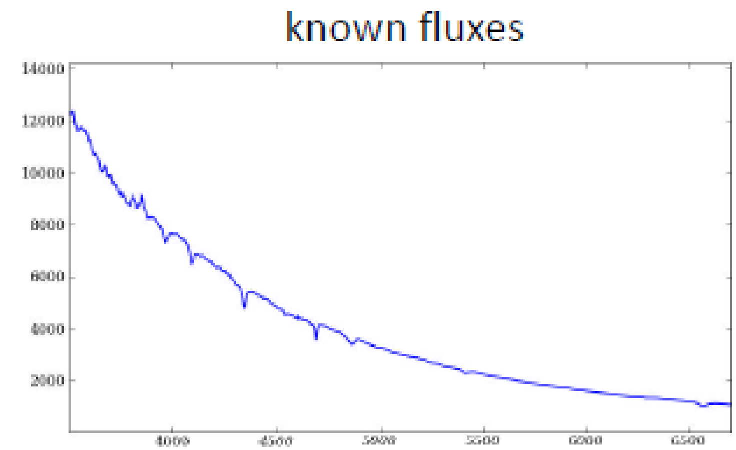
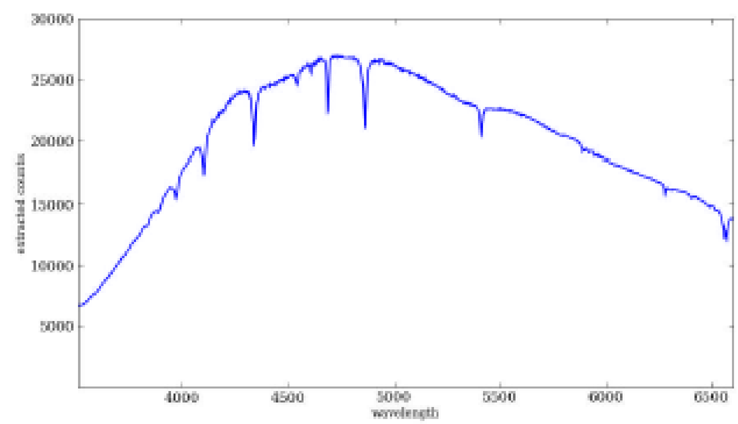


- Wavelength calibrate the science and standard spectra using the pix → λ transformation

Flux calibration

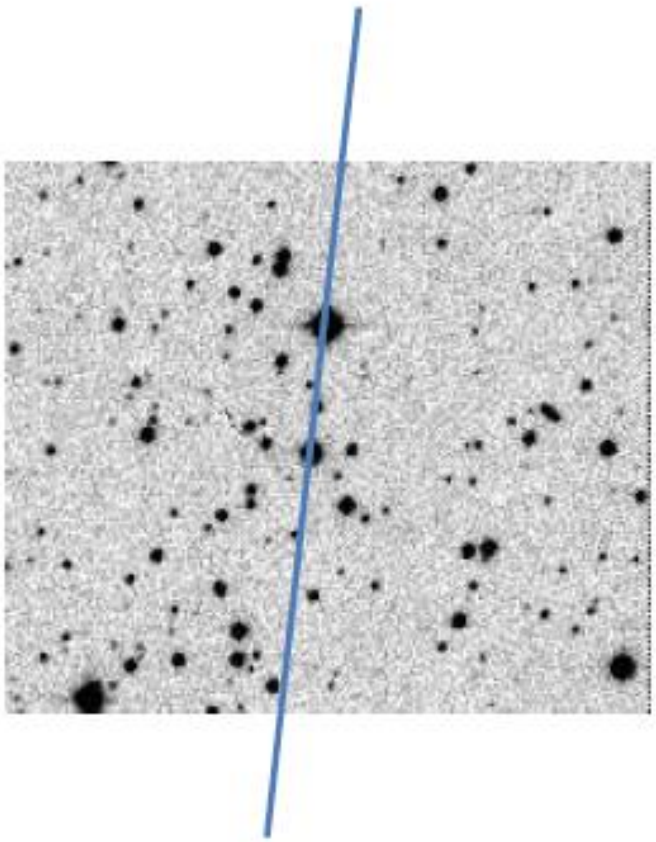
- This is a calibration of sensitivity and efficiency, and is carried out in the same way as the photometric calibration, by observing a number of standard stars whose flux as a function of wavelength is accurately known, at a variety of airmass values.





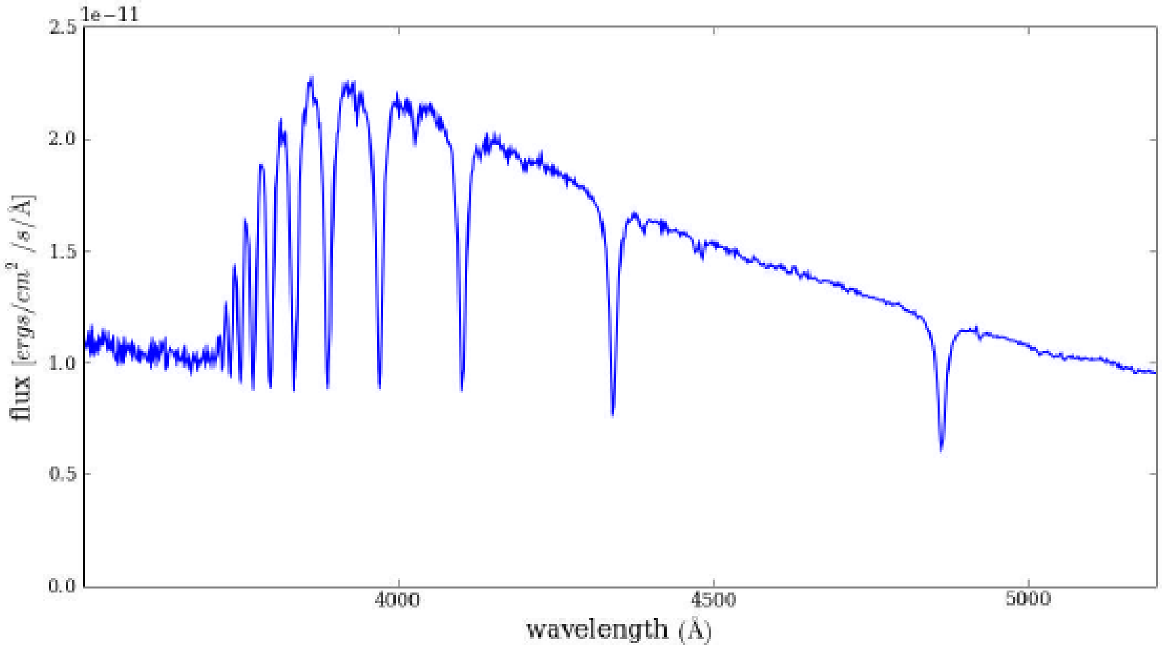
Flux calibration

- Flux calibration is subject to variable slit-losses since target observations are observed through a narrow slit
- A second reference star can be aligned to fall along the slit such that both target and reference star spectra can be extracted
- A differential flux correction can then be made by comparing the narrow slit observations with a wide slit observation of the reference star
- This requires the slit-angle to be fixed, and thus not be at the parallactic angle!



“Final” spectrum

Flux calibration of the science spectrum



- Velocity rest-frame: heliocentric frame
- Extinction/telluric correction

Now the fun can begin: velocities, abundances etc.