OBSERVATIONAL ASTRONOMY

AUTUMN 2023

Lecture 13

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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 spectral lines.
  - To measure the spectral energy distribution of the continuum radiation.

Practical spectroscopy (2)

- 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 calibration 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 (1)

- 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 (2)

- Index of refraction: $n(\lambda, T, p, f)$
  - wavelength, temperature, pressure, water vapour
- Angle displacement:

$$\Delta\theta = 206265 \times [(n_{\lambda 1} - 1) - (n_{\lambda 2} - 1)] \times \tan z$$

index of refraction

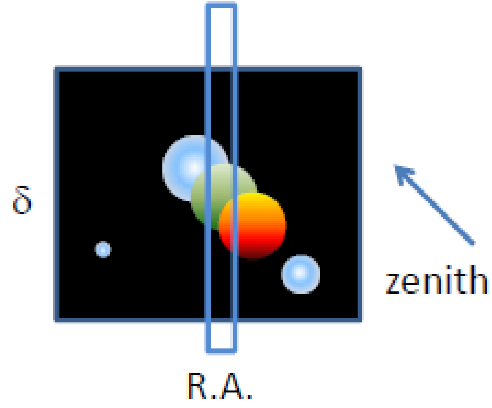
zenith angle (airmass)

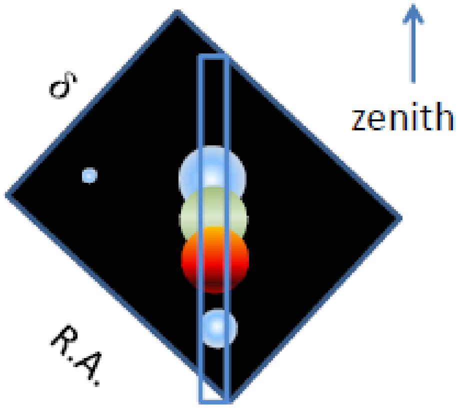
- Some example shifts (") relative to image at 5000Å:

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 (3)

- 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

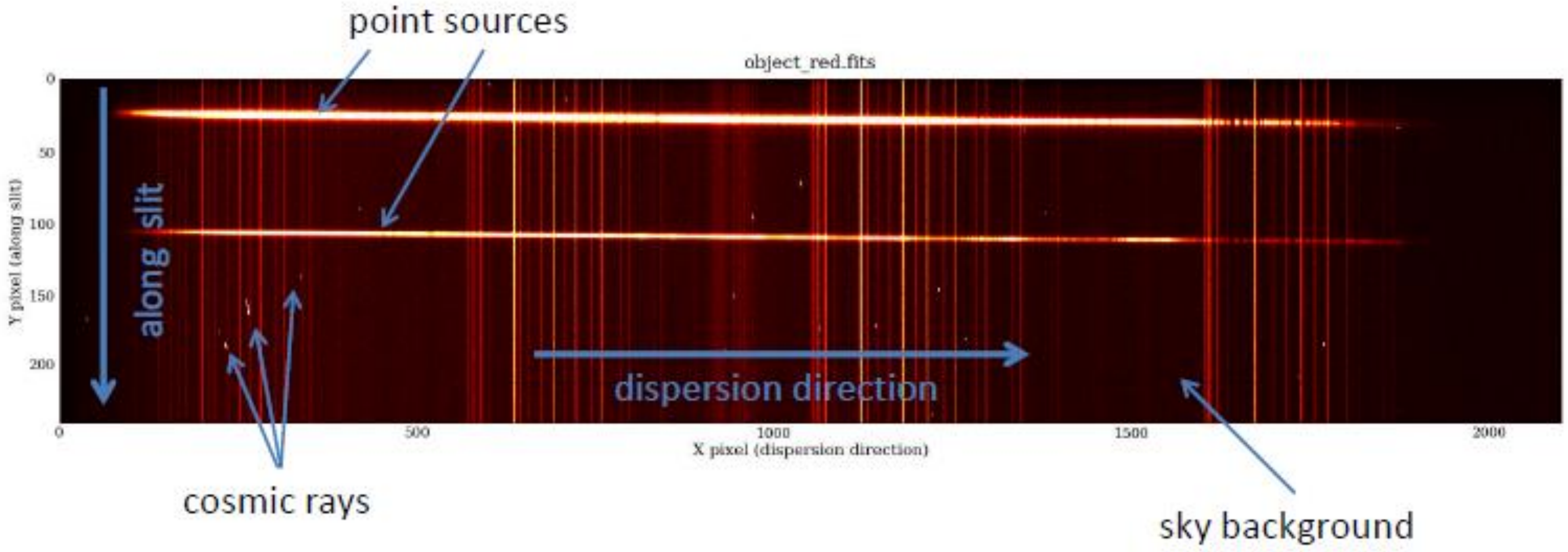




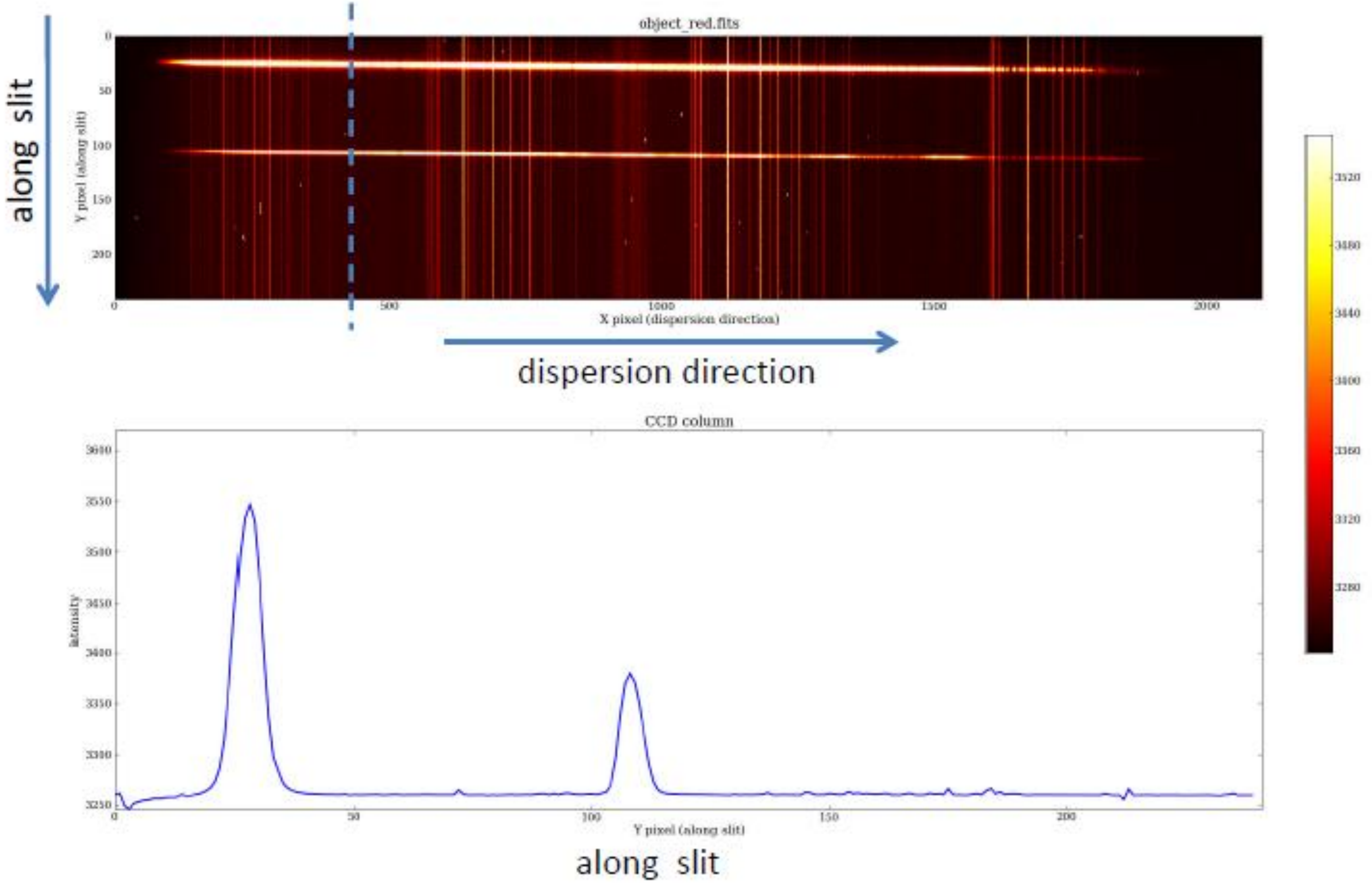
Calibration

- Primary reduction
- Extracting the spectrum
- Wavelength calibration
- Spectrophotometric calibration

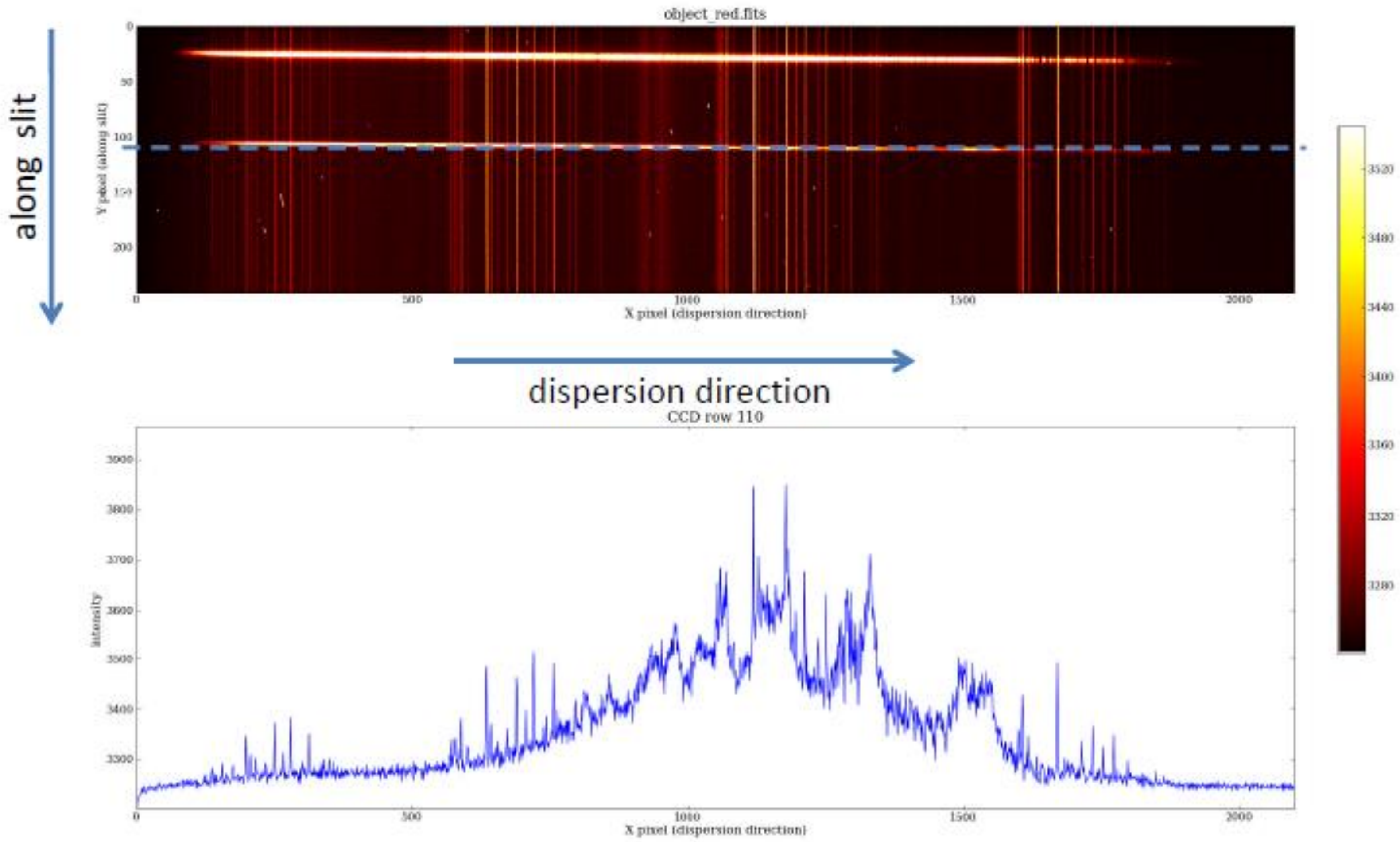
A long slit spectrum



A long slit spectrum: spatial slice



A long slit spectrum: spectral slice



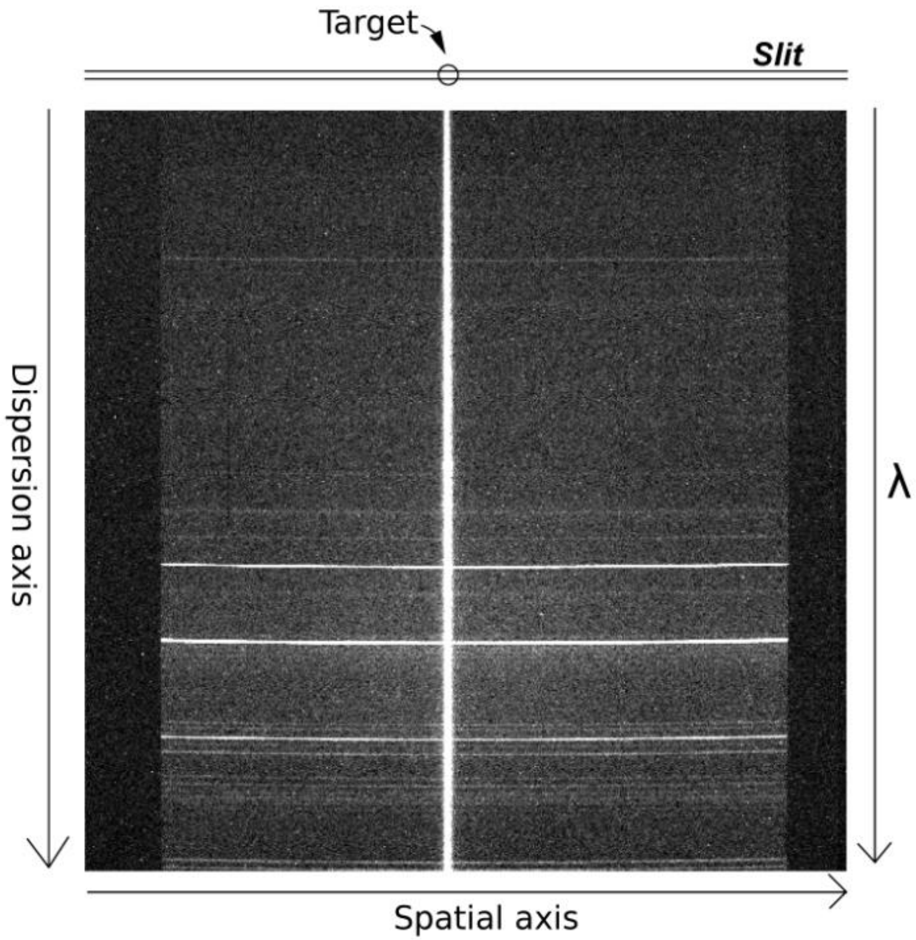
Reducing spectra

- 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

Calibrations: primary reduction

- 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. This step is not needed for photon counting detectors
  - 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.

An ALFOSC long slit spectrum

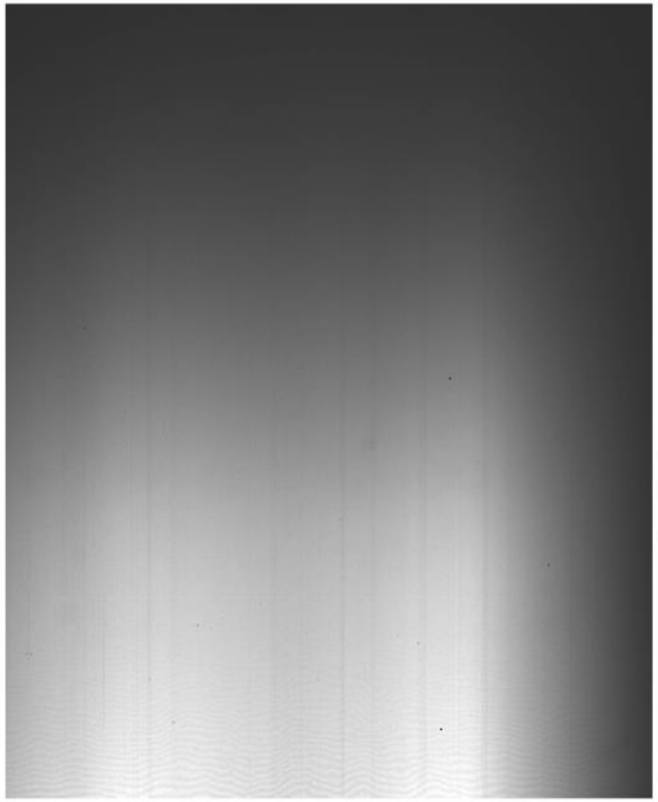


A simple rule:

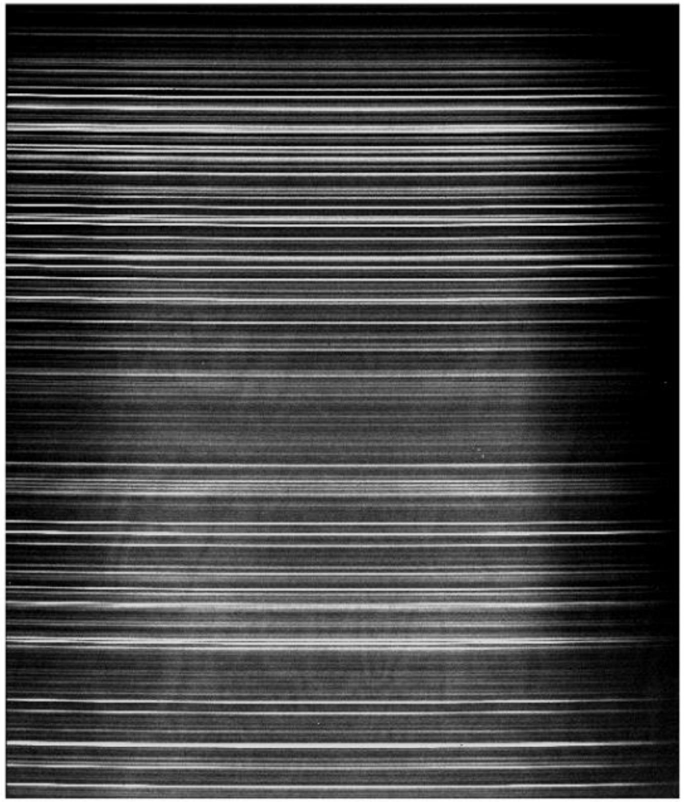
The spectrum on the CCD can be thought as the *image of the slit at different wavelengths*.

Calibrating spectra

Continuum lamp
(For flat-fielding)

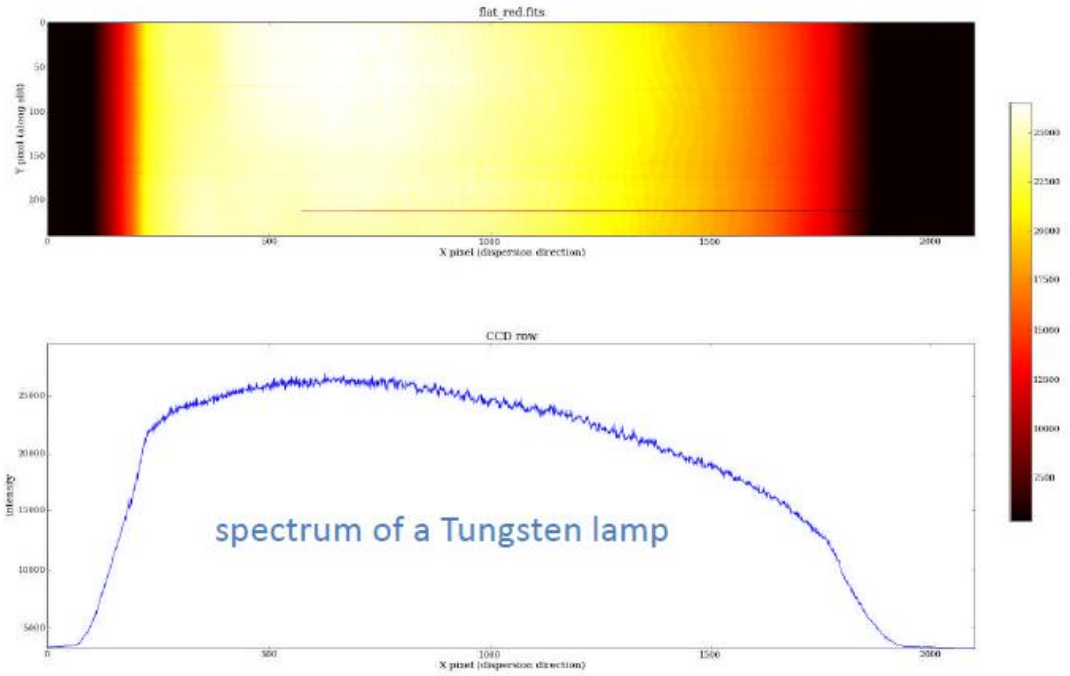


Line lamp
(For wavelength calibration)



Flat-fielding (1)

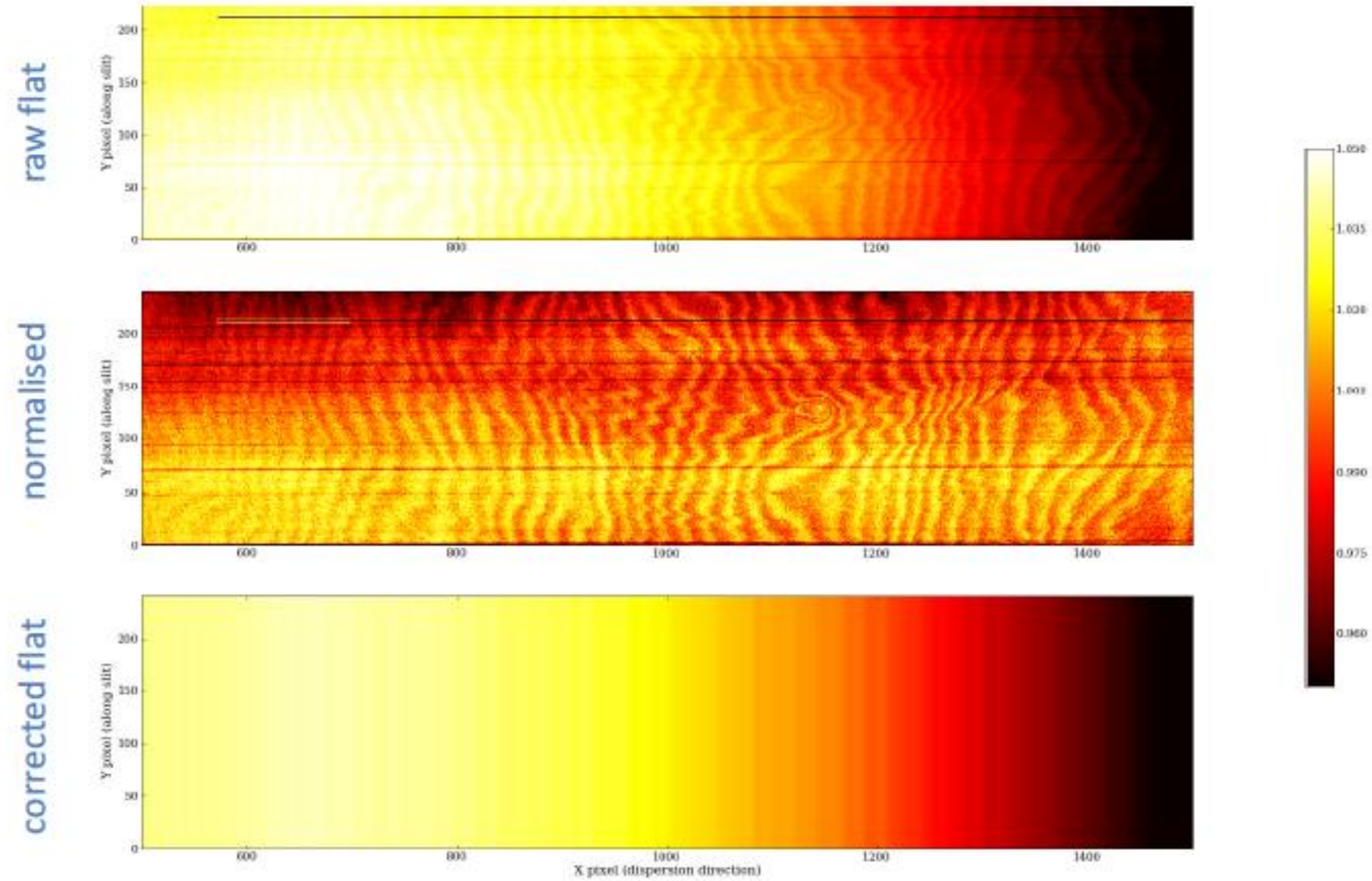
- Flat-fielding is probably one of the trickier steps
  - Uniform illumination along the slit
  - Uniform illumination along the dispersion direction
    - Need a light source with a smooth/simple spectrum



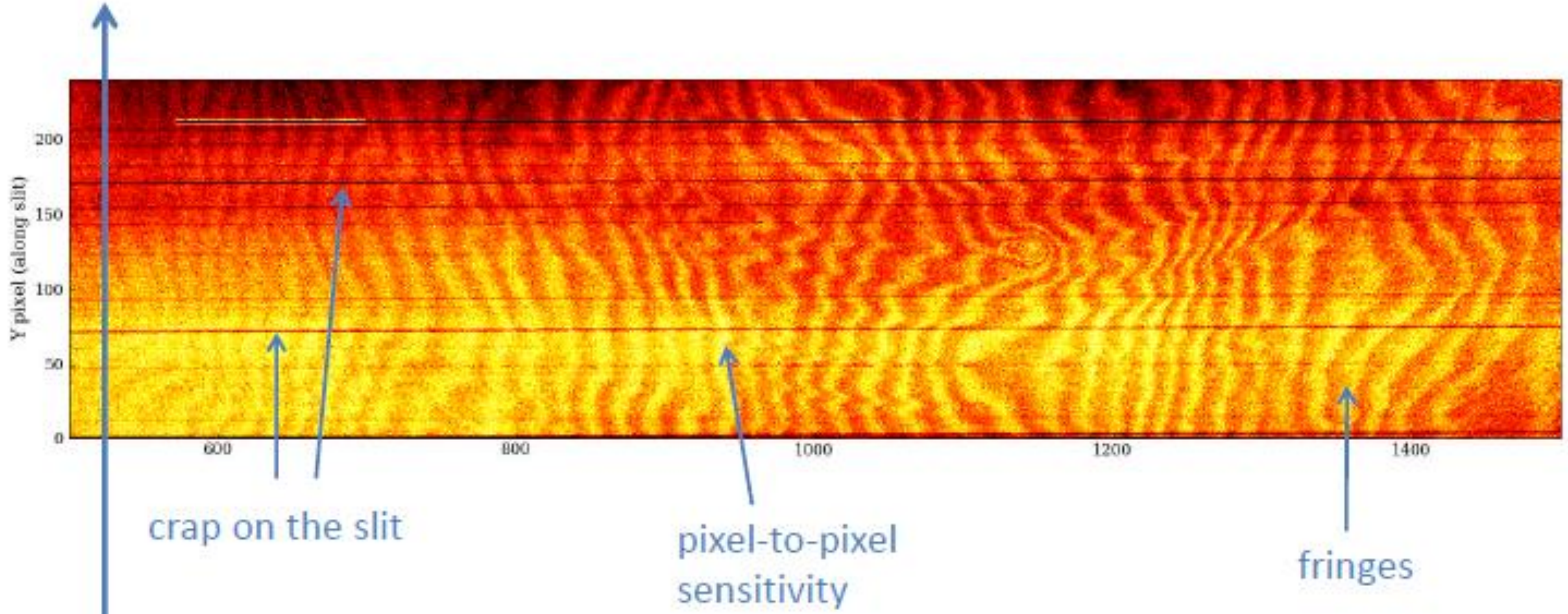
Flat-fielding (2)

- 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 (3)



Flat-fielding (4)



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

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

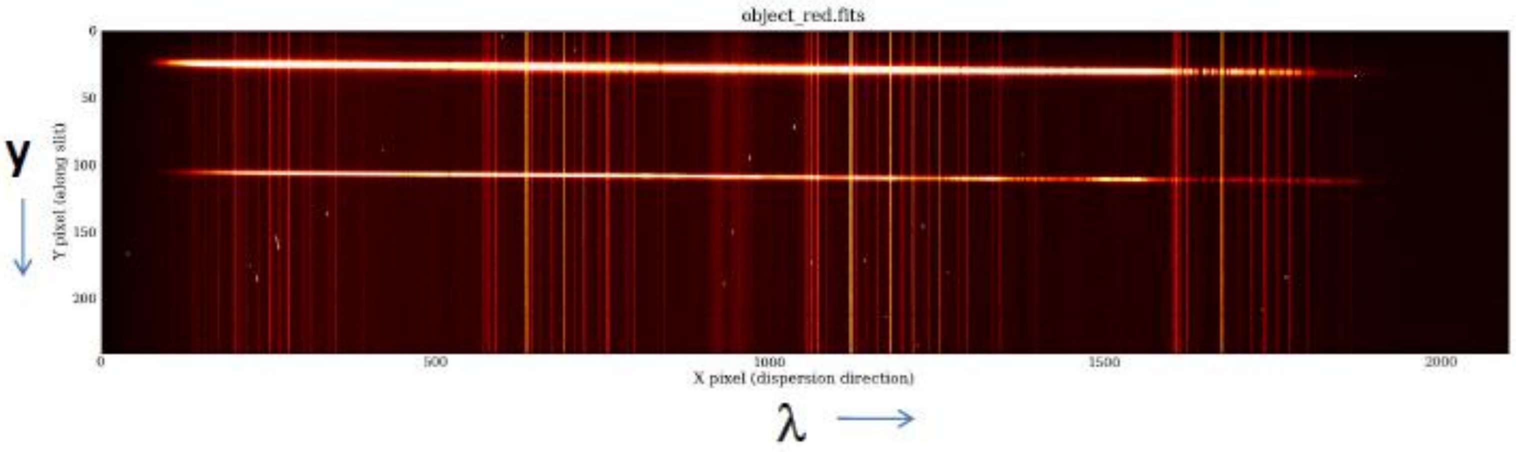
object profile weight (p(y))

sky profile weight (b(y))

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

relates λ to x,y

dispersion relation

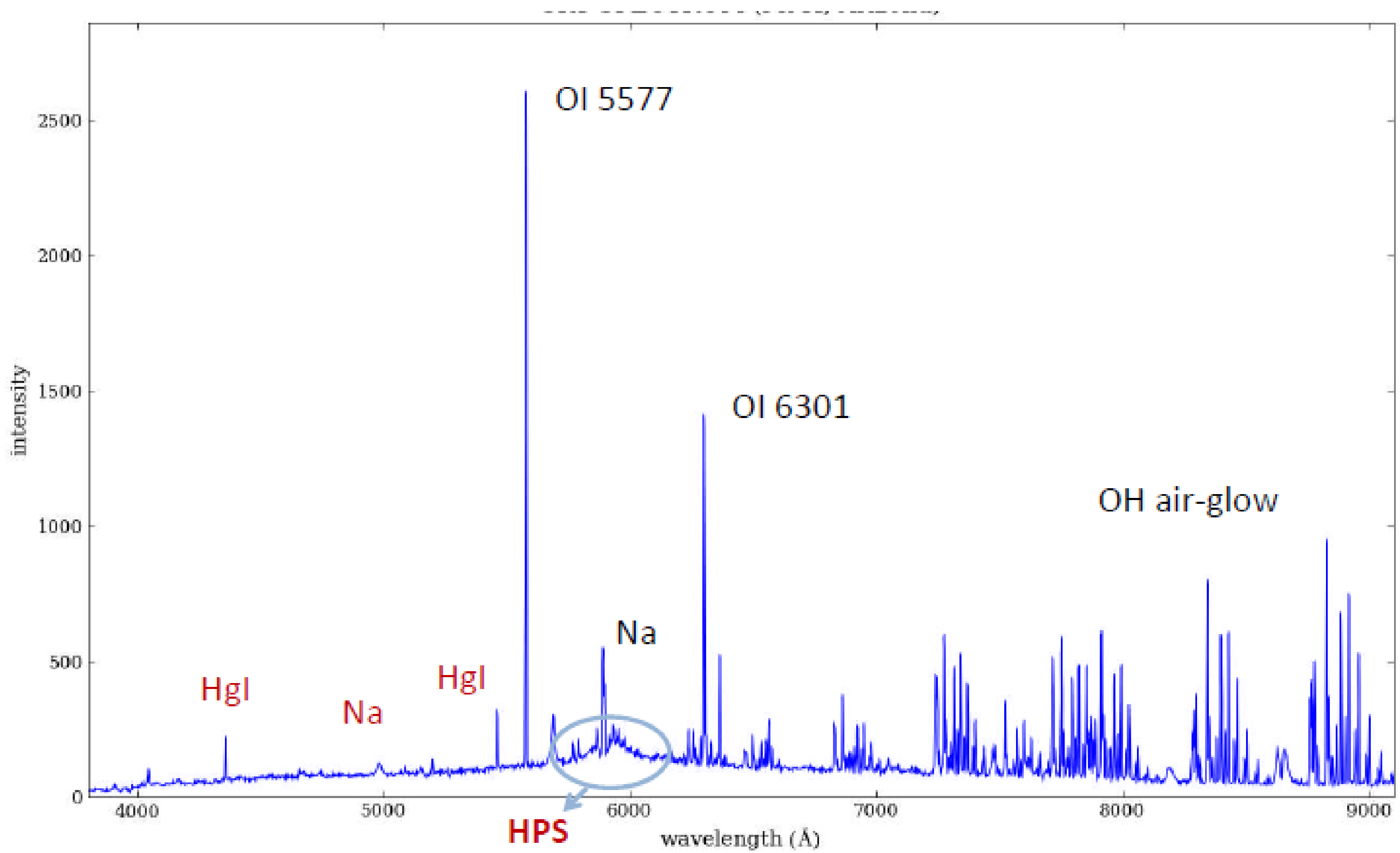


Sky background (1)

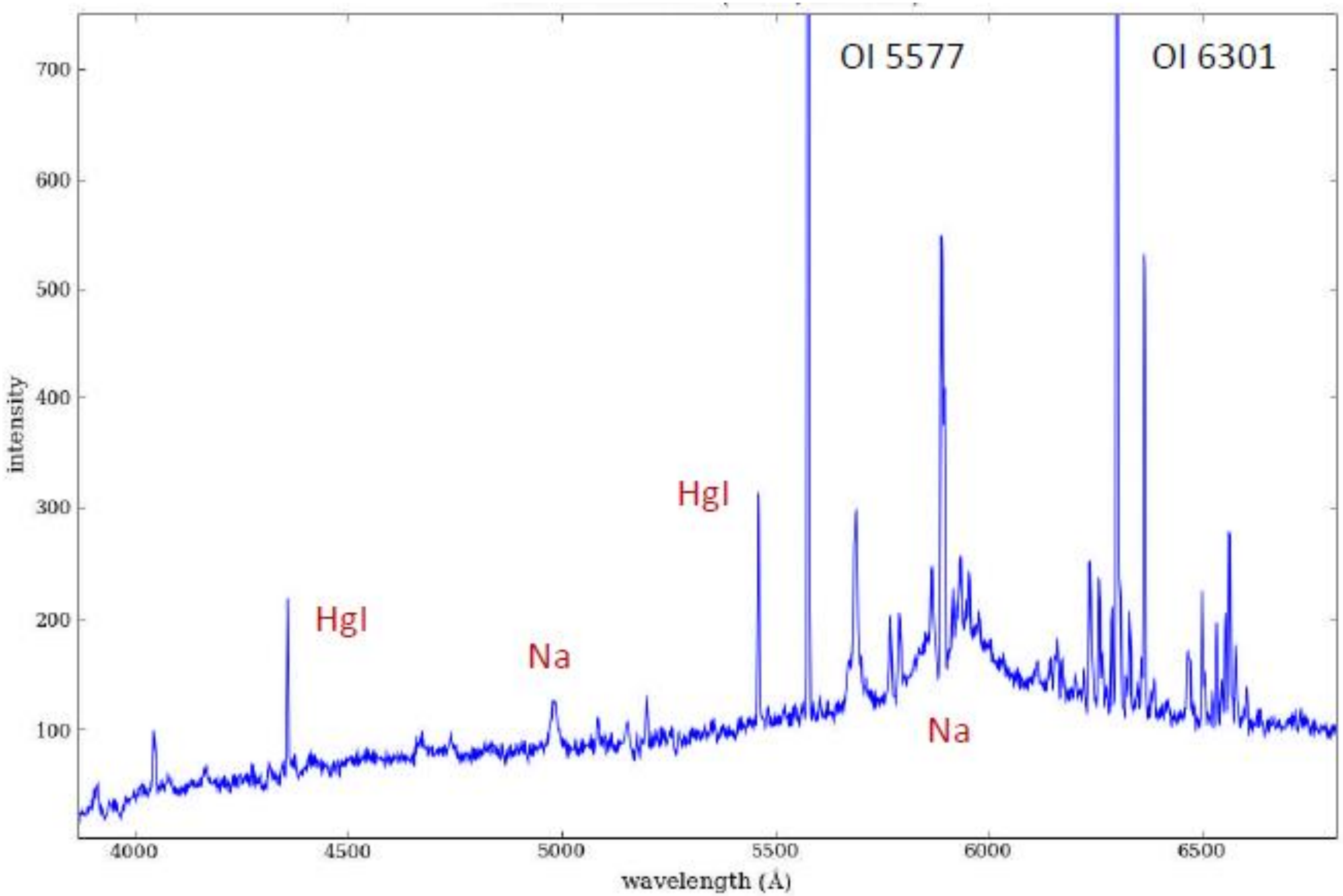
Background has contributions from many sources;

- 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 (2)

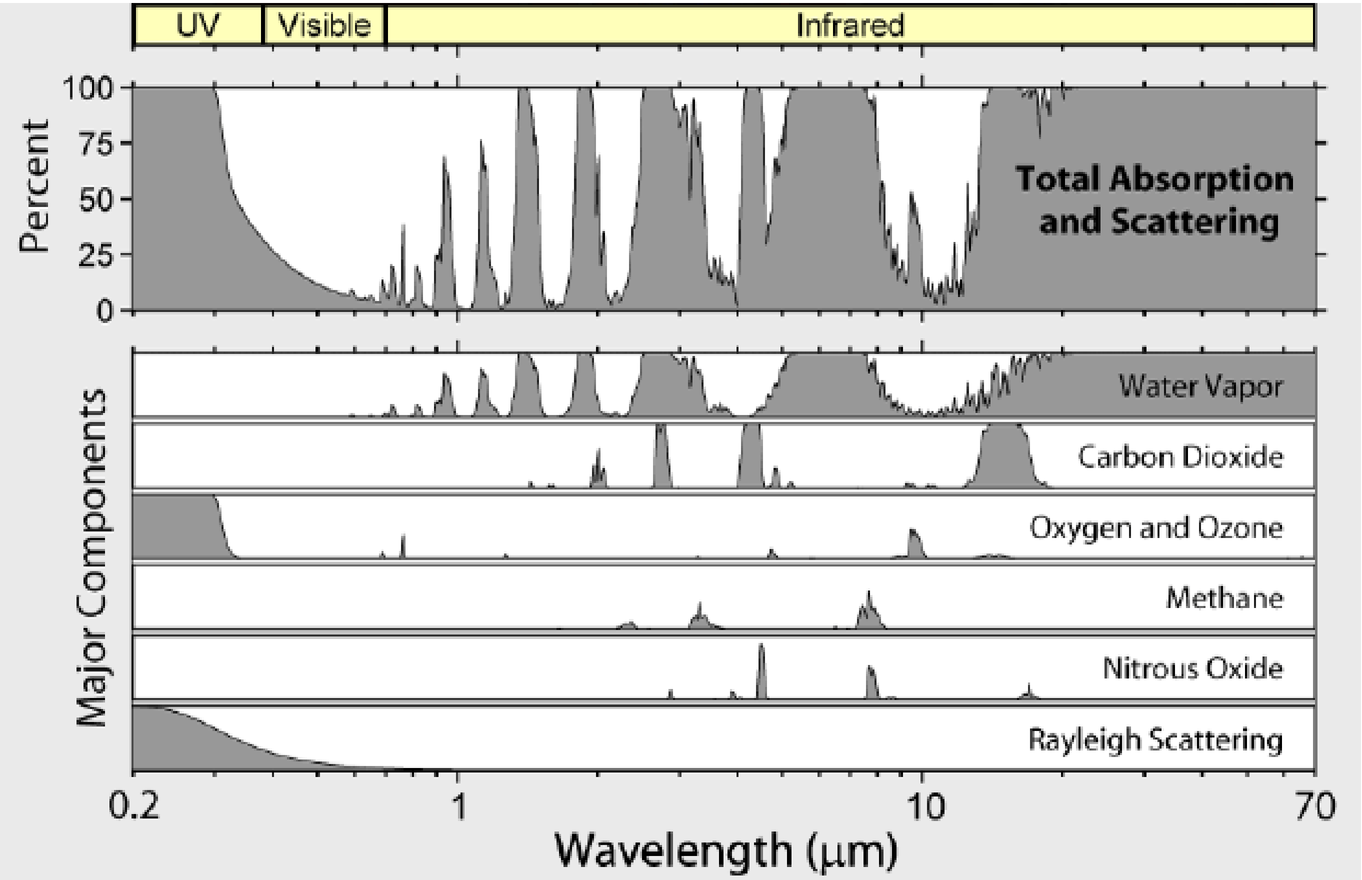


Sky background (3)

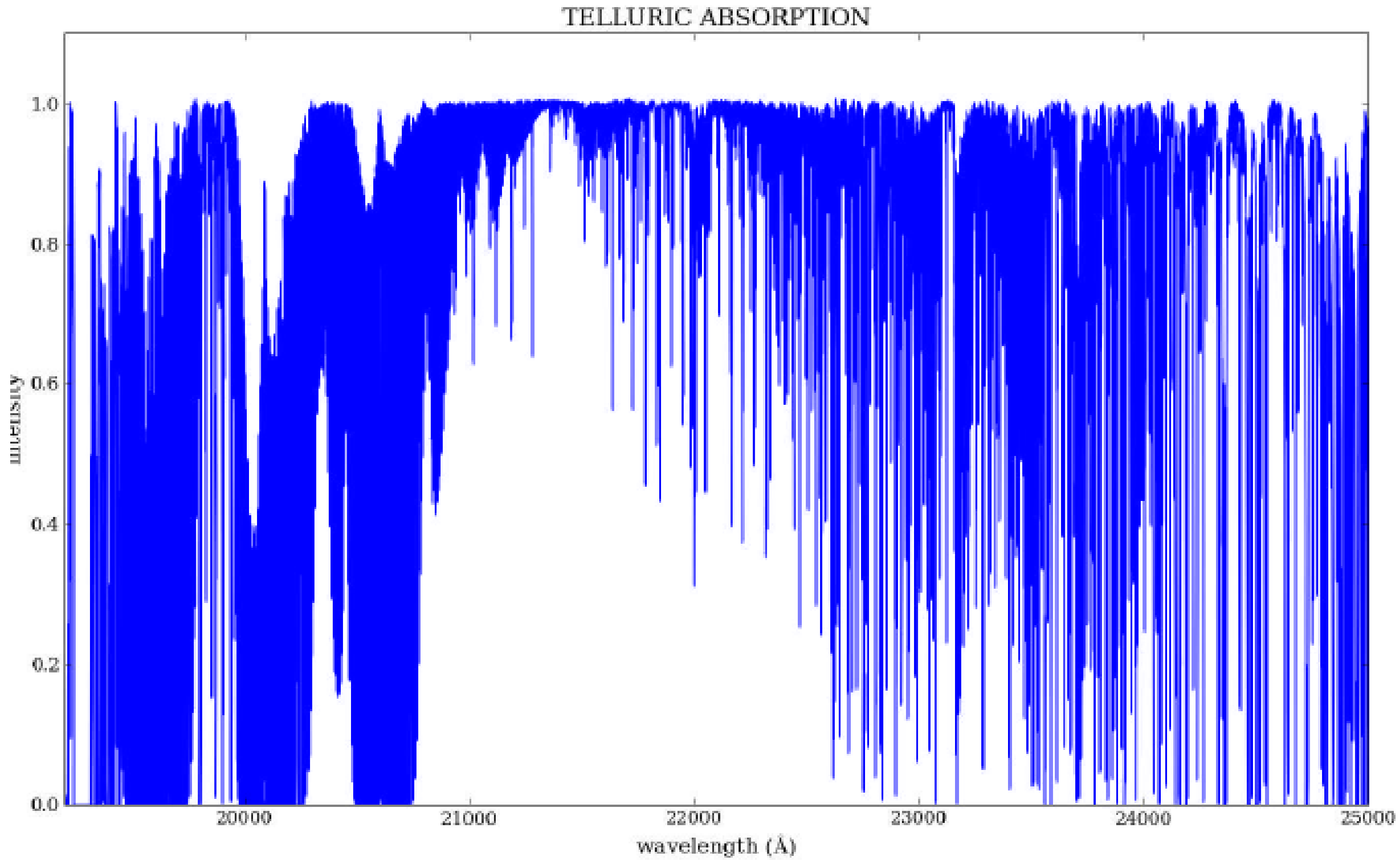


Atmospheric transmission

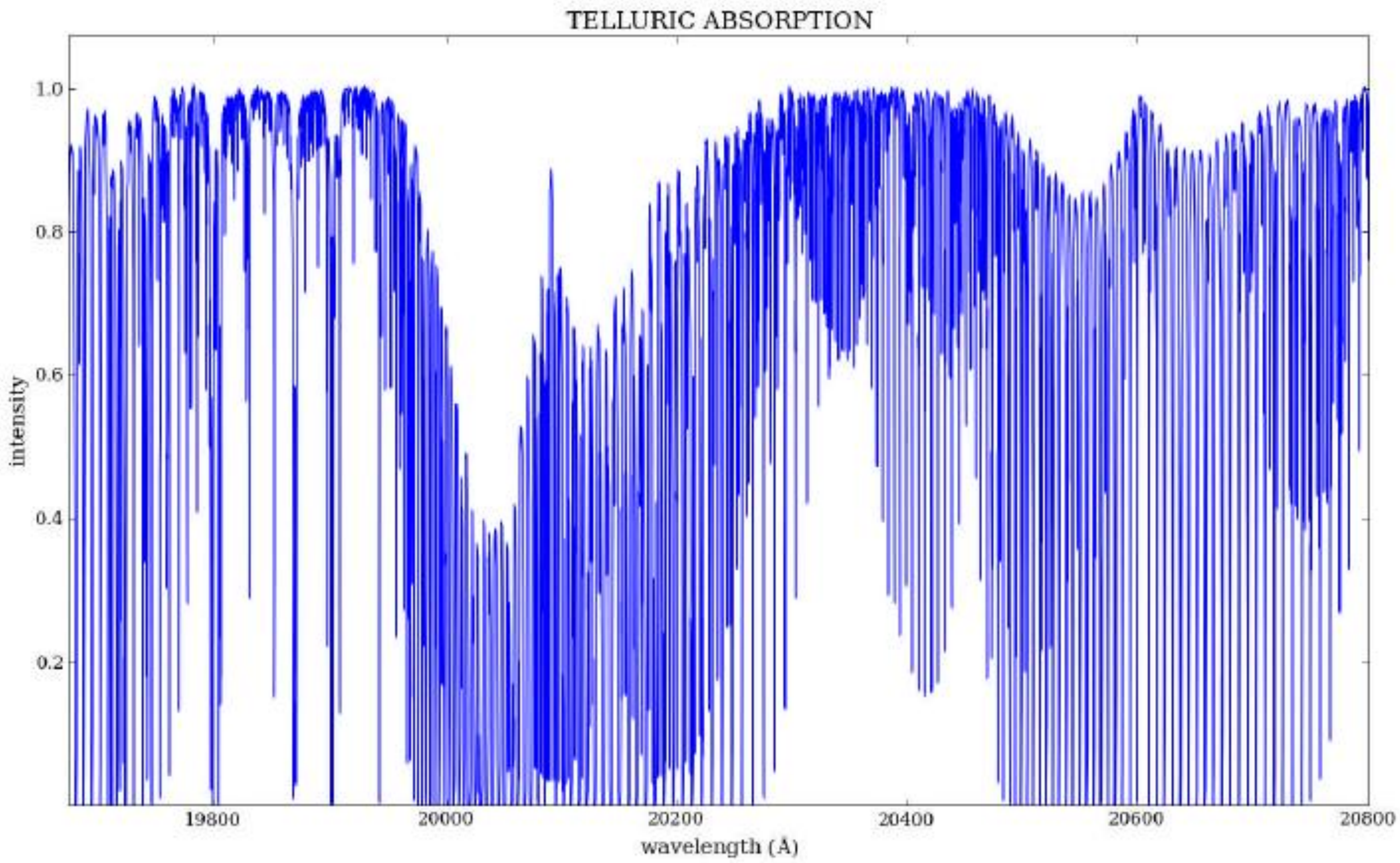
Atmospheric transmission is strongly dependent on wavelength



Telluric absorption (1)



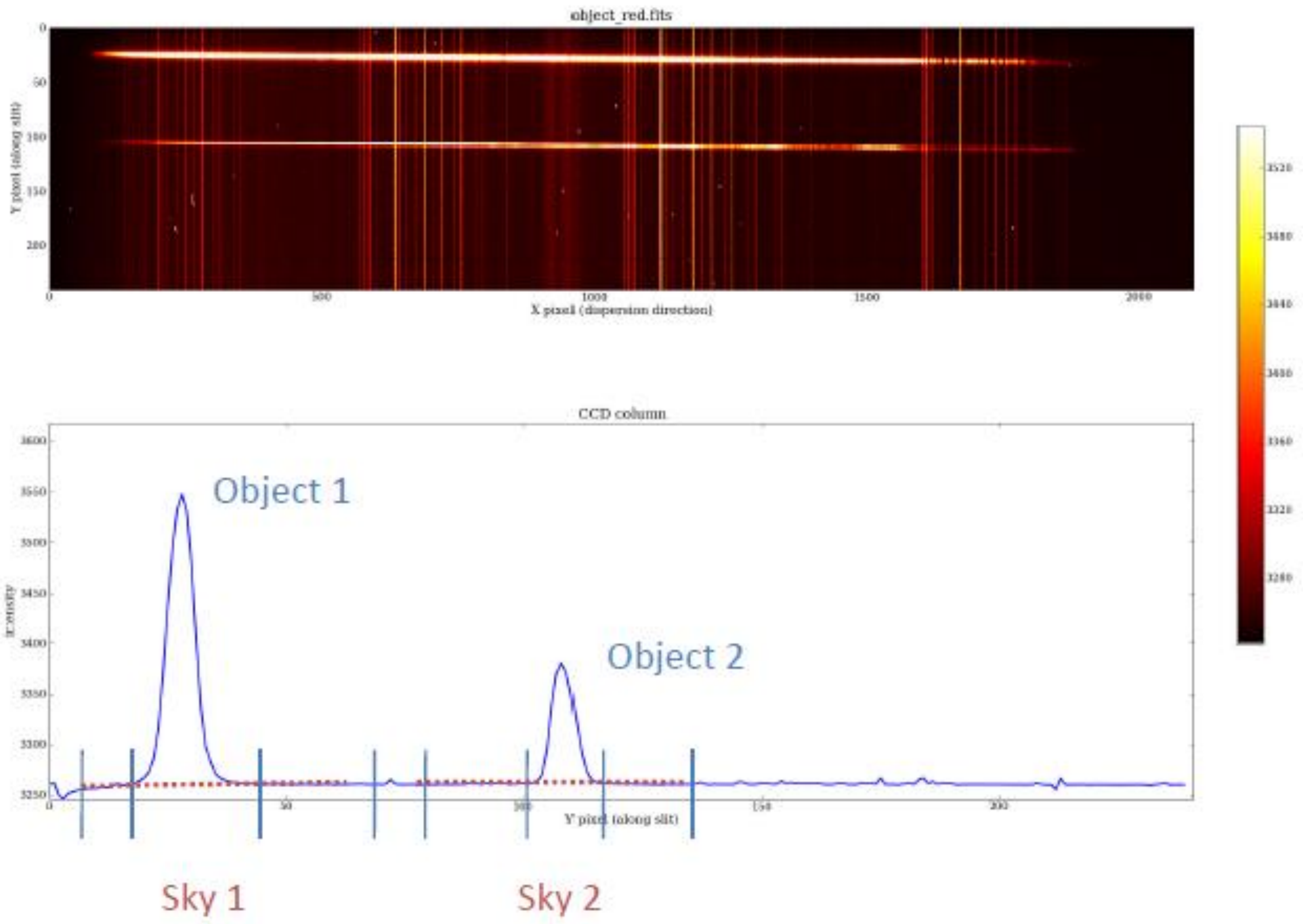
Telluric absorption (2)



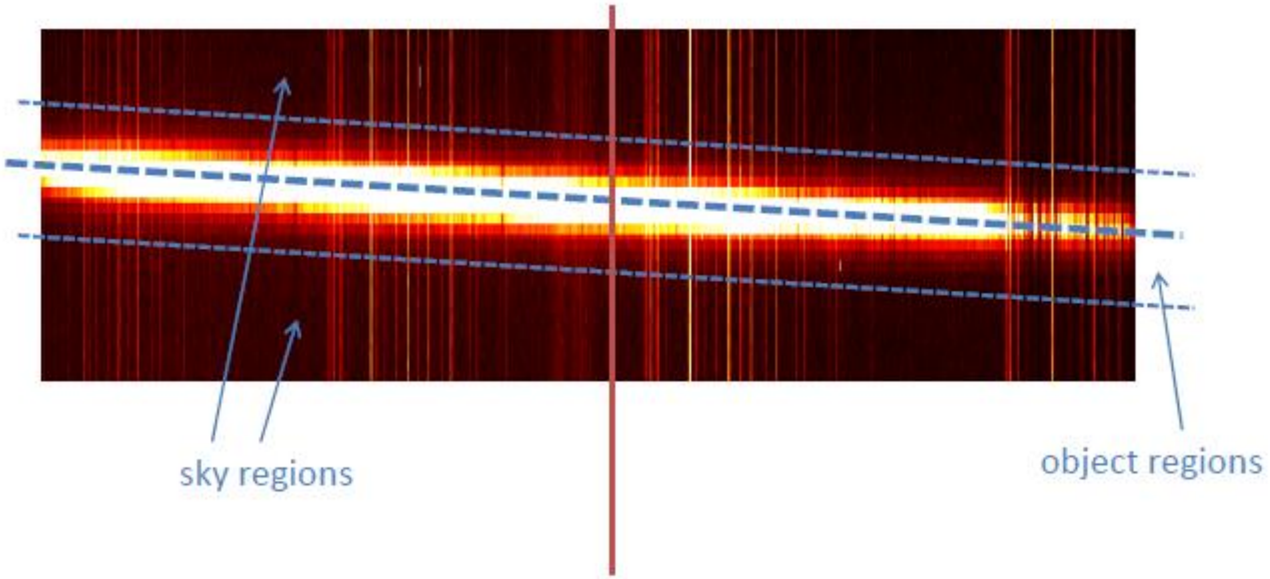
Summary: Background

- 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

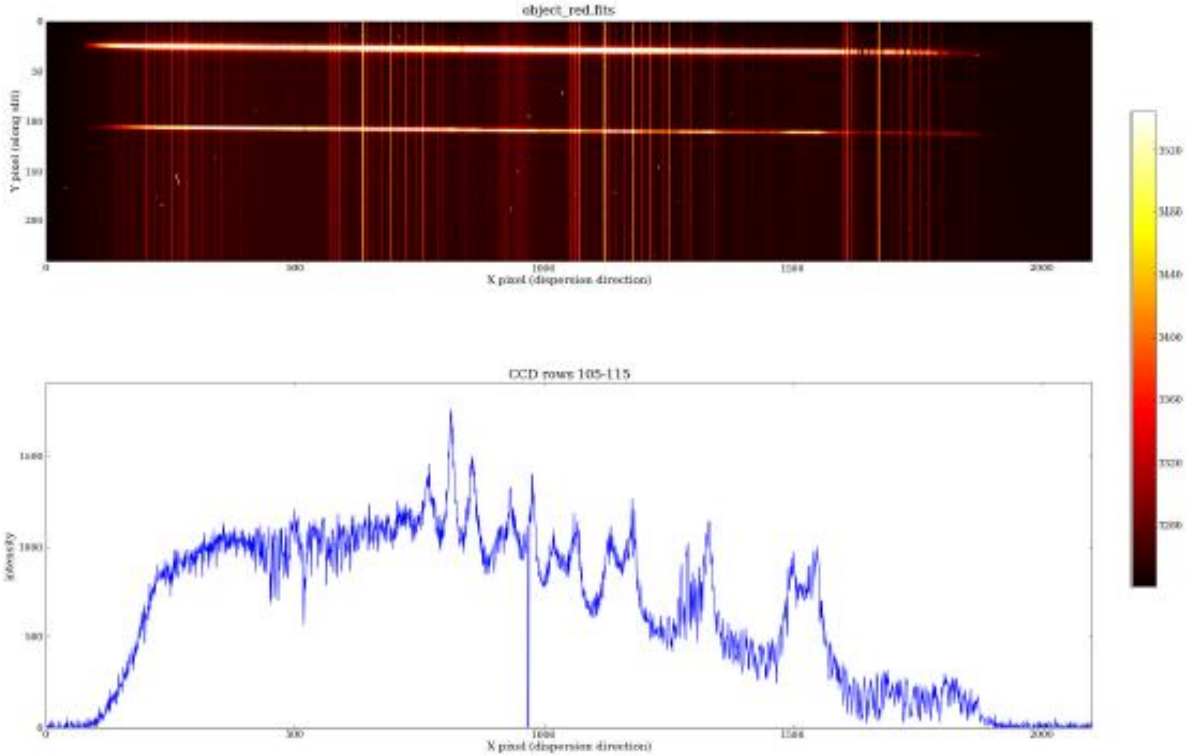


Tracing and skyfit



- 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: naïve method



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

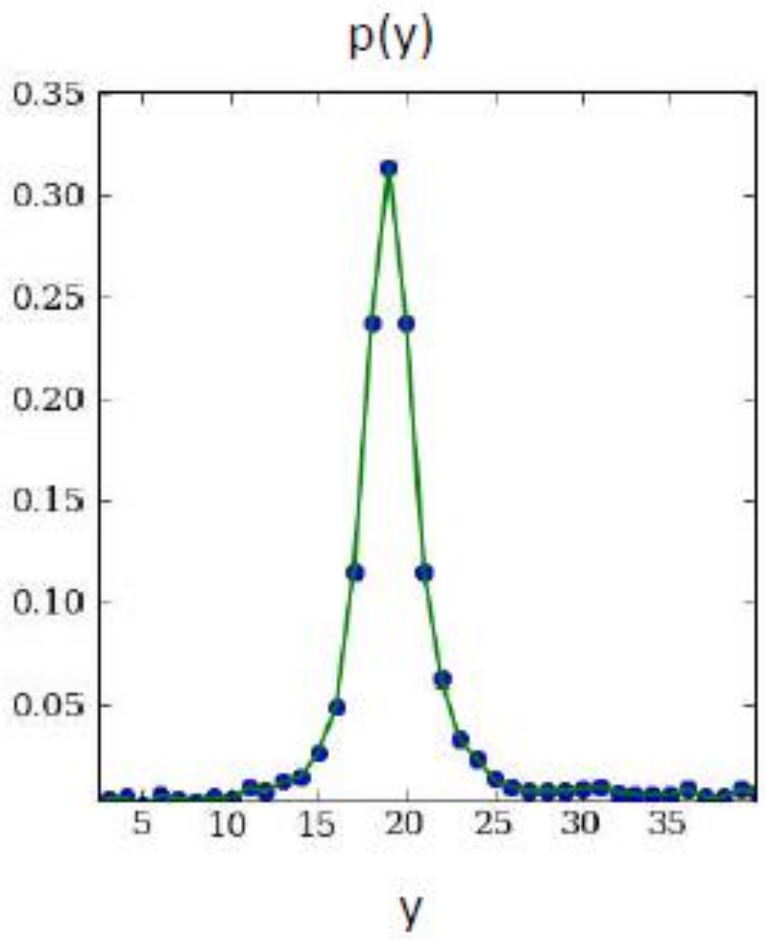
unweighted sum over object region

skyfit at each object pos

Net signal: optimal extraction (1)

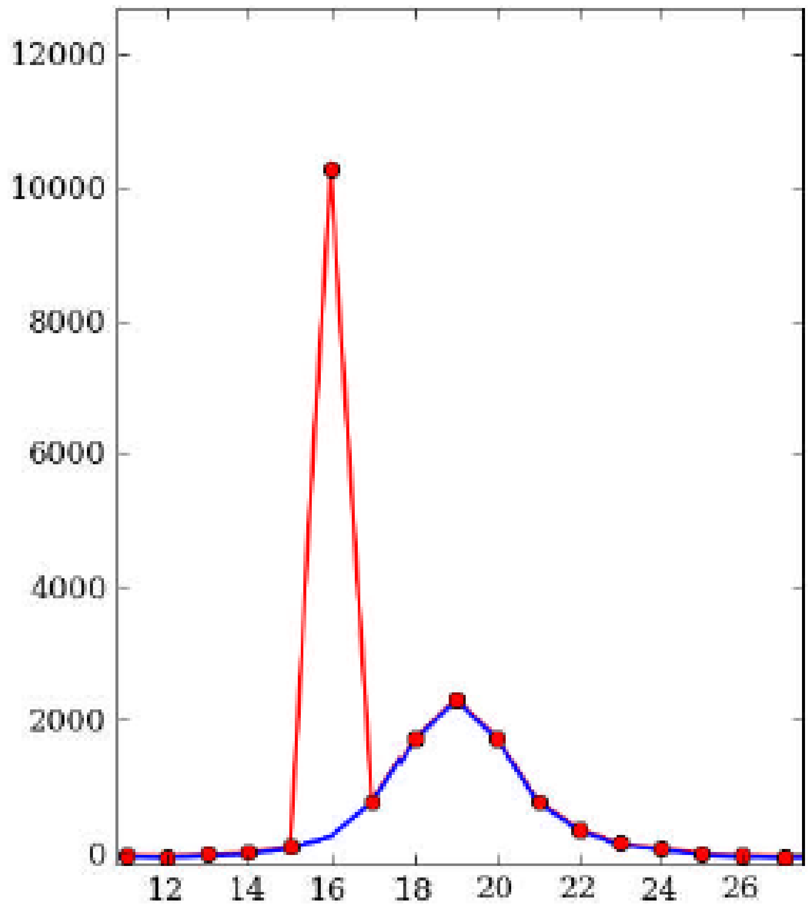
- Optimal sum across the object profile considers the fractional contribution of a given pixel to the total light at that wavelength and weighs its contribution
- Profile p(y) is measured from the 2D frame and normalised such that Σ p(y) = 1 when summed along the extraction region
- Optimal weights (minimising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

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



Net signal: optimal extraction (2)

- 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



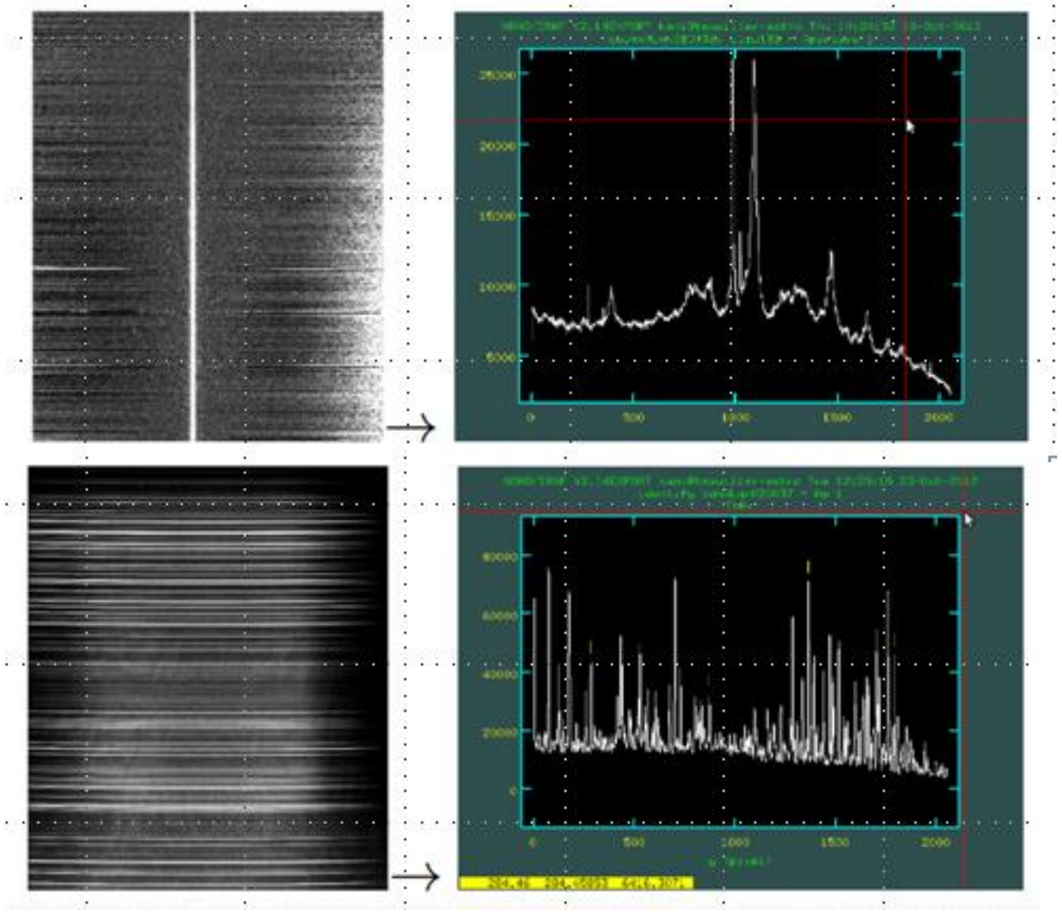
Wavelength calibration (1)

- **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 (2)

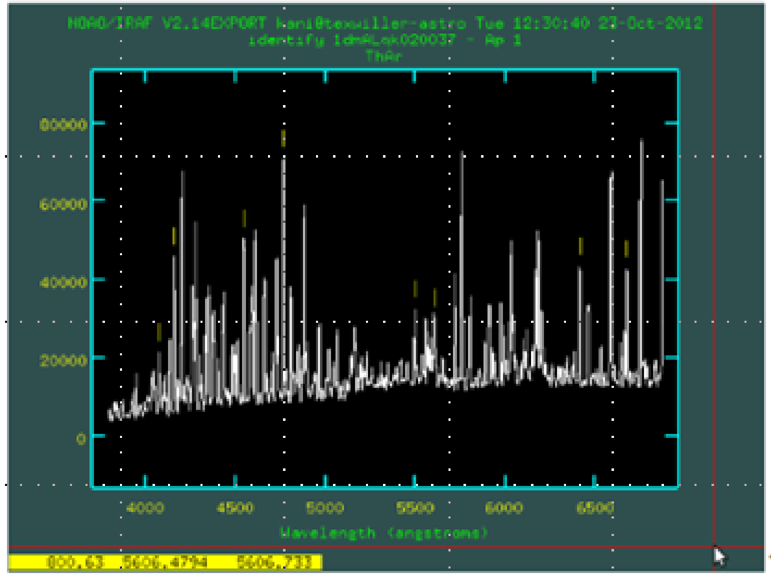
Extract the 1-d spectrum of the star

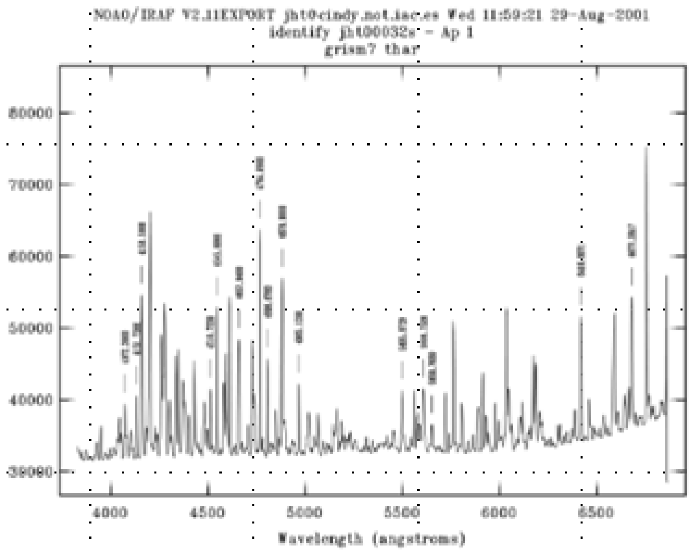
Extract the lamp (arc) spectrum



Wavelength calibration (3)

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





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

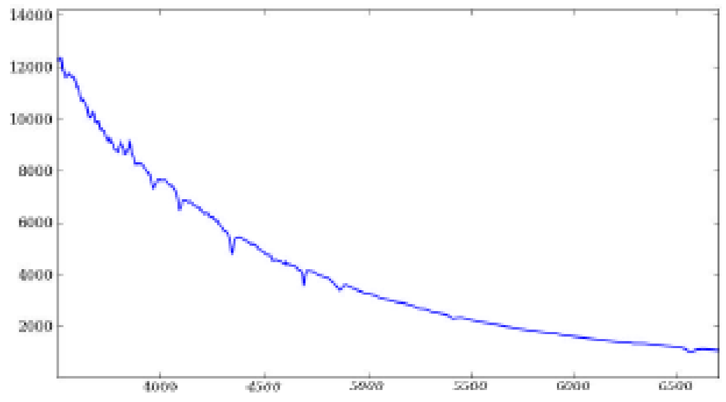
Spectrophotometric calibrations

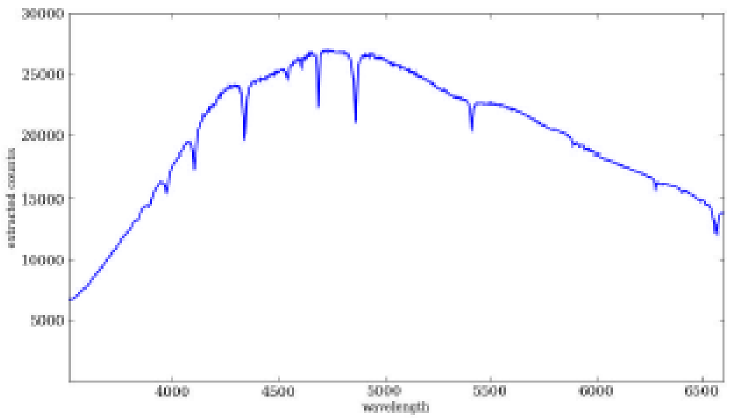
- **Spectrophotometric calibration or Flux calibration.** This is a calibration of sensitivity and efficiency, and is carried out in the same way as the photometric calibration, by observing a number of standard stars whose flux as a function of wavelength is accurately known, at a variety of airmass values. There is one extra quite serious problem.
  - The slit size α is set so that the size projected on the detector p is of order 2 detector pixels, this gives the maximum spectral resolution. α is normally smaller than the resolution set by seeing, so light is lost at the entrance slit.
  - The amount of light lost varies between exposures, making an absolute flux calibration very difficult.
  - The amount of light lost is also wavelength dependent, due to the weak dependence of seeing on wavelength, and due to atmospheric dispersion.

Flux calibration (1)

- 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.

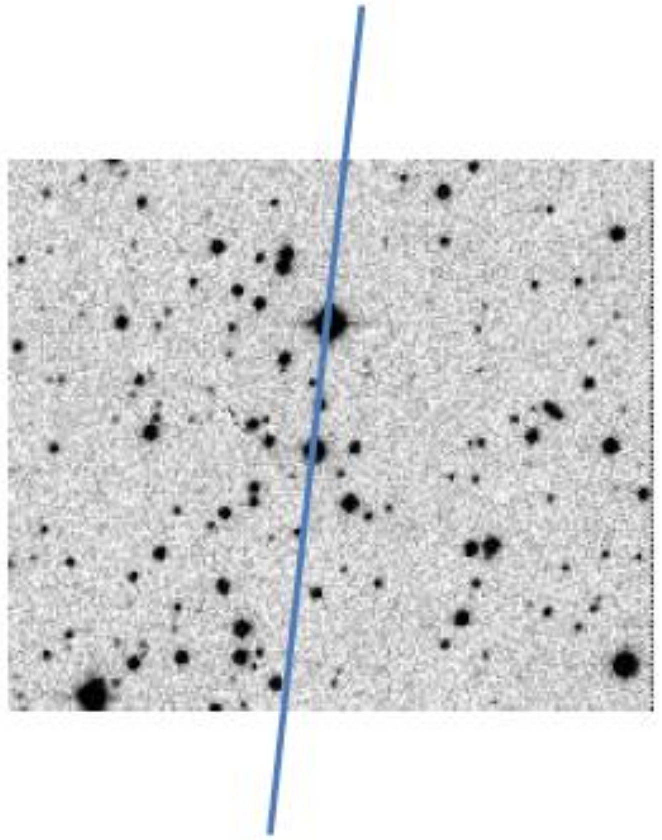
known fluxes





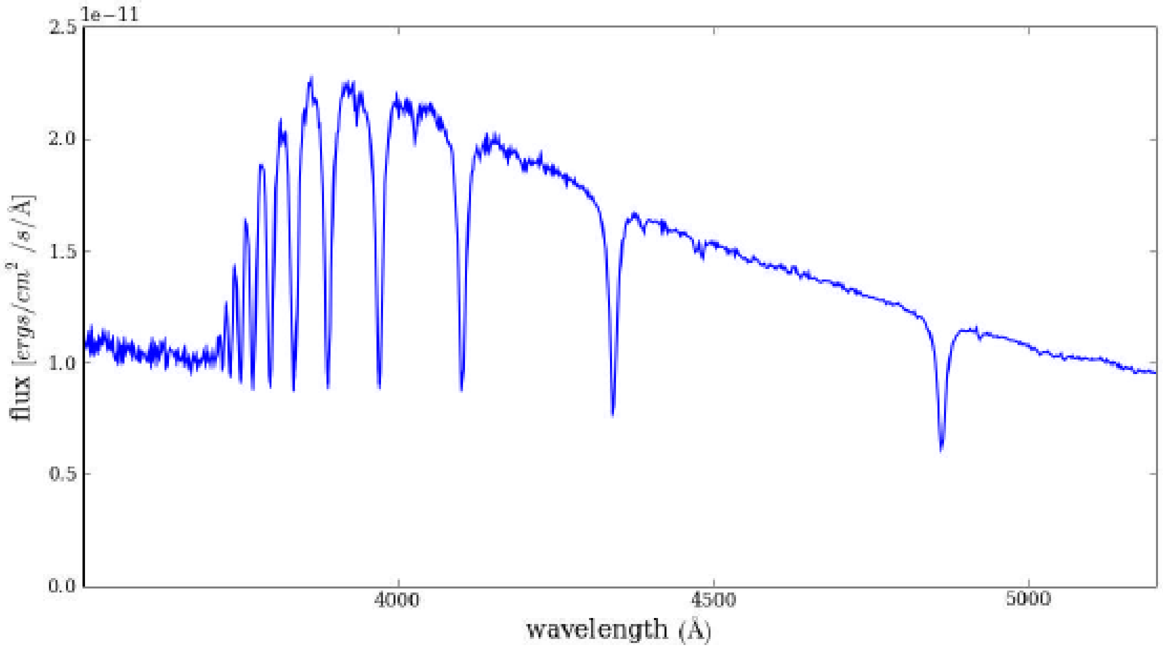
Flux calibration (2)

- 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.