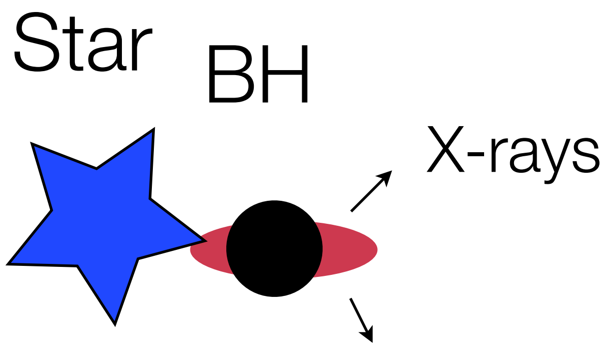
Readings for Lecture

From Gallaway "*An Introduction to Observational Astrophysics*":

PS#9 is posted in full. Due Dec 20th.   Reading Week hours posted.

X-ray Binary System



<u>Close separation binary</u>

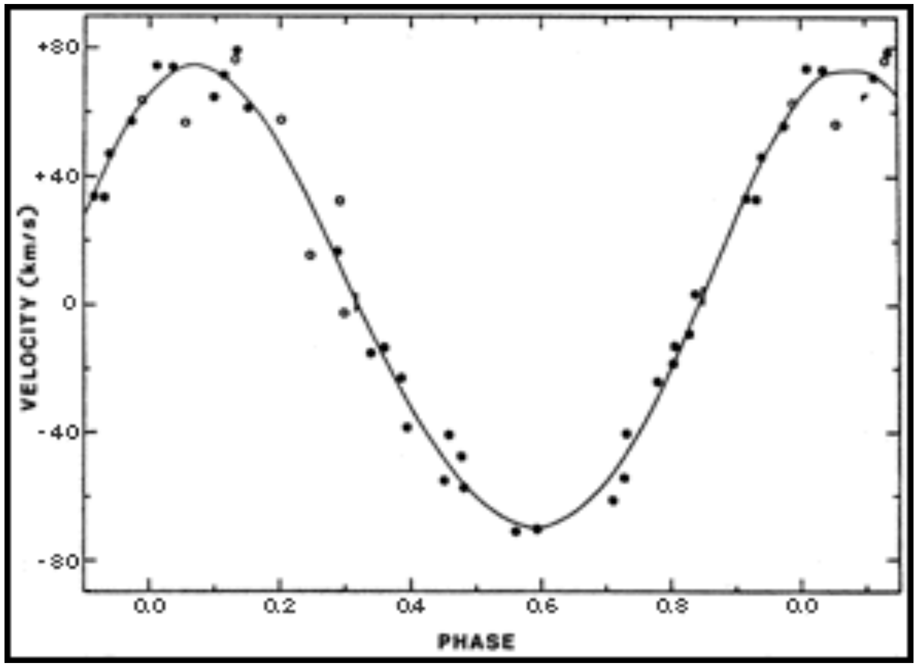
X-rays emitted as gas heats.
All known stellar mass black holes discovered via X-rays

<u>Wide separation binary</u>

No X-rays.
Black hole cannot be ‘seen’.

Try to infer based on optical velocities

Black Hole in Cygnus X-1



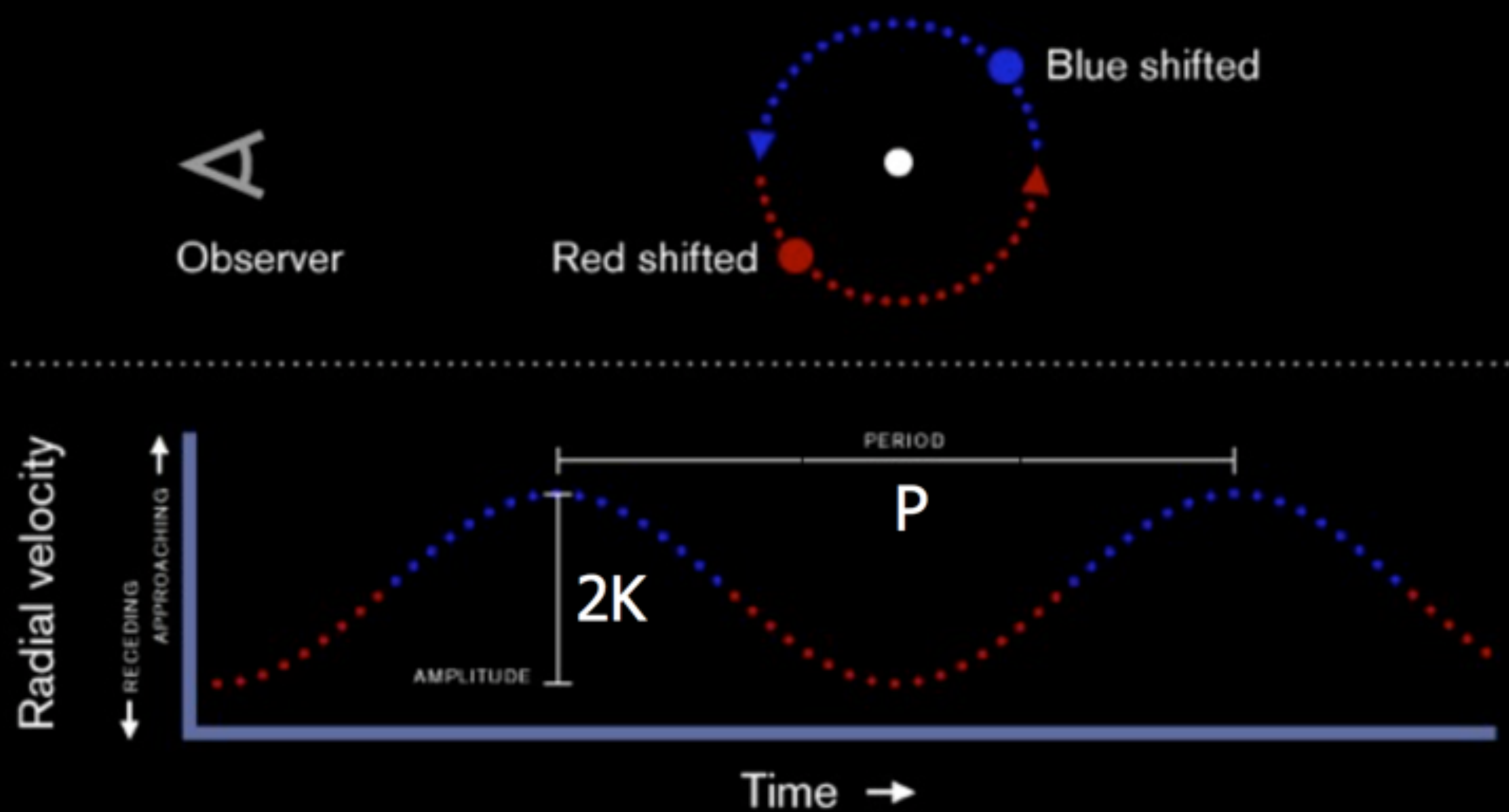
First (and best) case for a black hole M_{BH} = 7-13 M_{sun}.

Radial velocity curve of bright star in Cygnus X-1.

No companion observed.

How is mass determined from these data?

DETERMINING MASS OF COMPACT OBJECT IN X-RAY BINARY



AMPLITUDE = 2 x MINIMUM VELOCITY

Determine mass of a Compact Object in a Binary System

Measure: P = period
K_2 = Velocity amplitude of luminous star

Kepler's Law

$$a^3 = \frac{P^2 G(M_1 + M_2)}{(2\pi)^2} \quad = \frac{P^2 G M_1 (1+q)}{(2\pi)^2}$$

M_1 = Unknown object's mass
M_2 = Luminous star's mass
a = semi-major axis
q = M_2/M_1

For any orbit $$V = \frac{2\pi a}{P}$$

however, we only observe motion of second star
$V_2 = (1 + q)\, V$

And we are viewing orbit from an unknown inclinat
$K_2 = (1+q)\, V\, (\sin i)$

Determine mass of a Compact Object in a Binary System

Putting this all together:

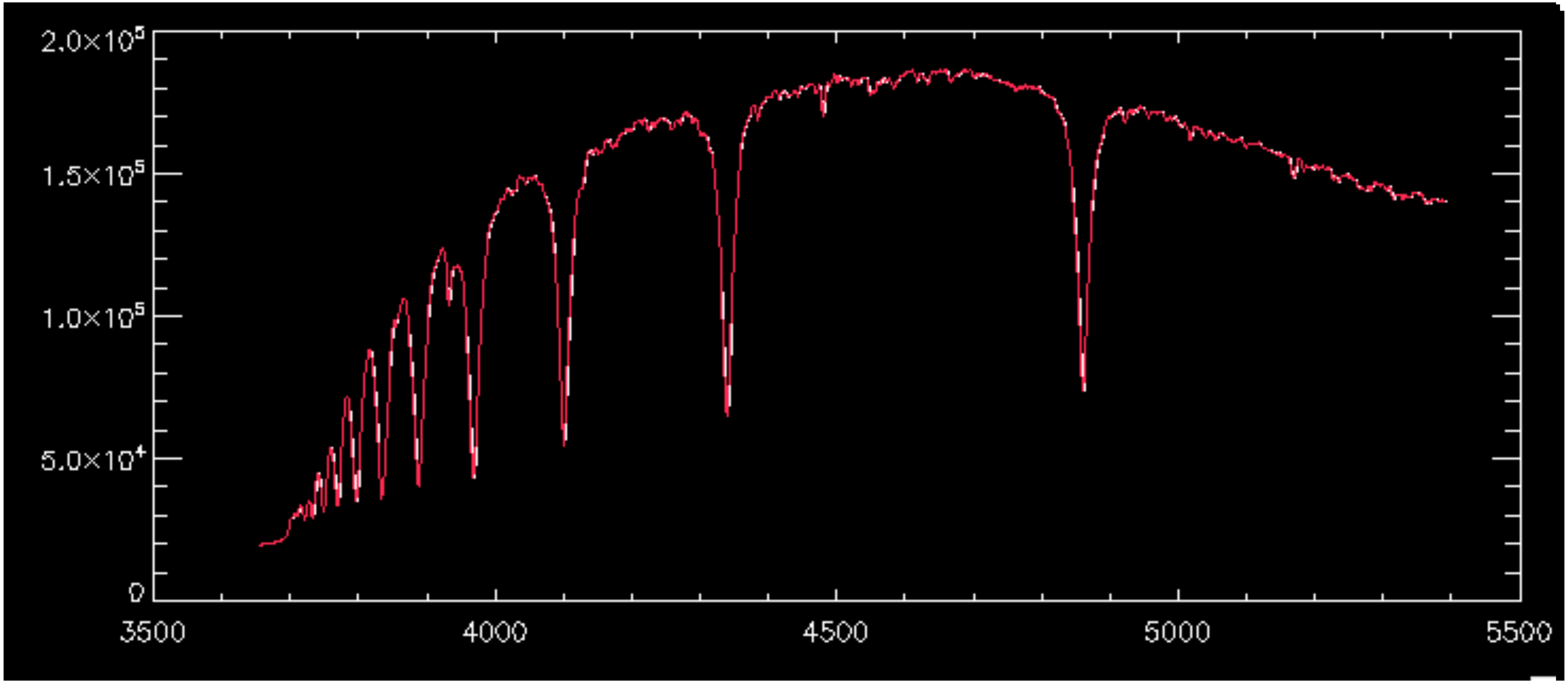
M_1 = mass of compact object

$$\frac{K_2^3 P}{2\pi G} = \frac{M_1 (sini)^2}{(1+q)^2}$$

Can measure all of this

Let's assume inclination sin i = 1
Can estimate mass of luminous star from its spectrum.

Spectral Lines: Chi^2 fitting

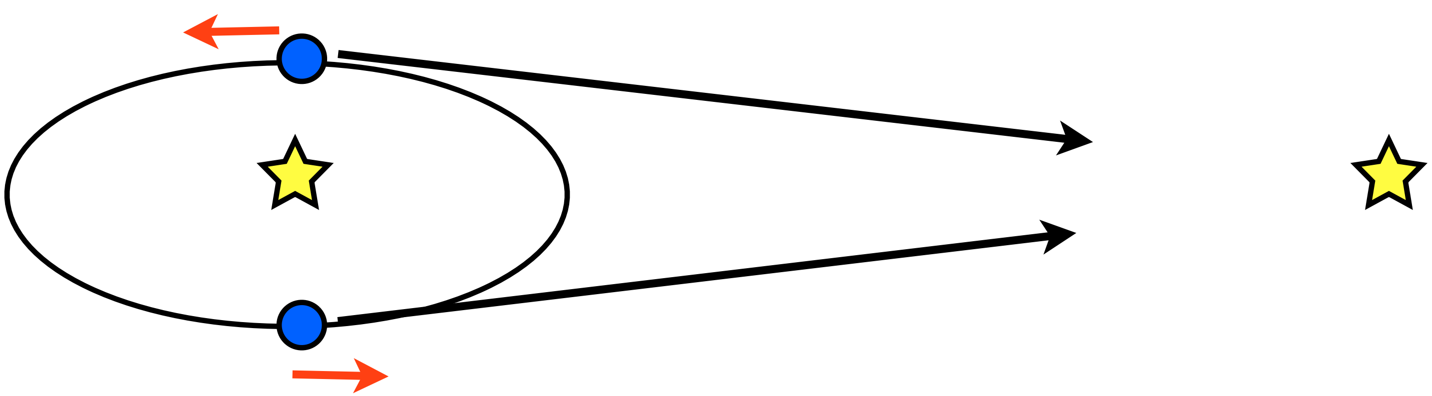


Velocities are in the Earth-centric frame, depends on when/where you observe!

Reducing Spectra - Heliocentric Correction

Velocities are usually reported in the rest frame of the Sun.

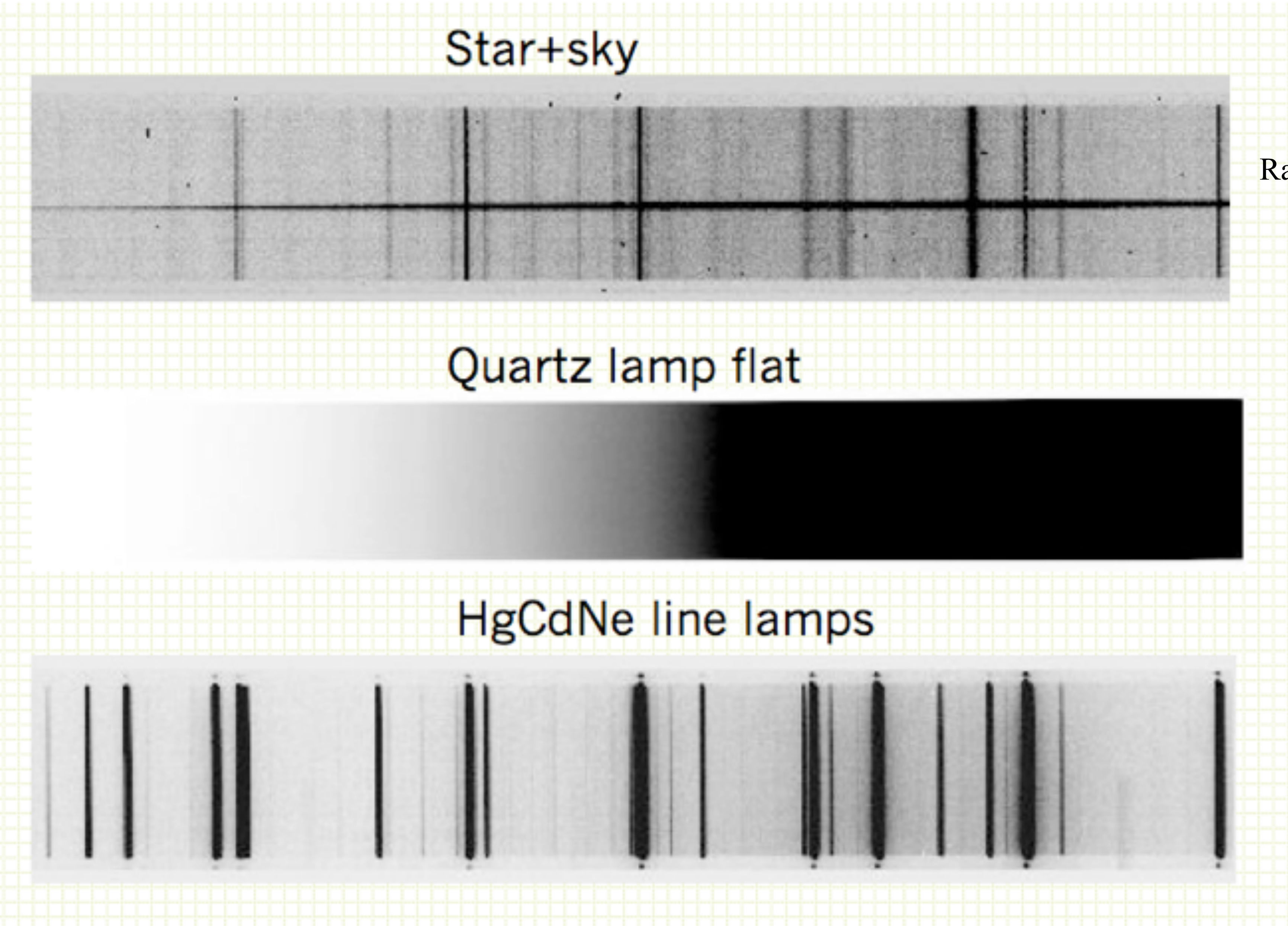
The Earth's motion on its axis and around the Sun introduce velocity shifts which we can correct if we know the exact time of the observation.



Heliocentric correction is at most 20 km/s (optional step: prove this statement), and can be calculated given the observation time/date and position on Earth.

JD = Julien date

Reducing Spectra



Raw Science spectrum

Spectral Flat Field

Arc lamp

Reducing Spectra

1. **Normal CCD processing**: Bias and dark subtraction

2. **Flat fielding**: ``Flatten'' spectra in both the wavelength and spatial directions.

3. **Wavelength calibration:** Use arc lamps with known lines. Identify lines, determine line centers and fit function to centers vs. wavelength.

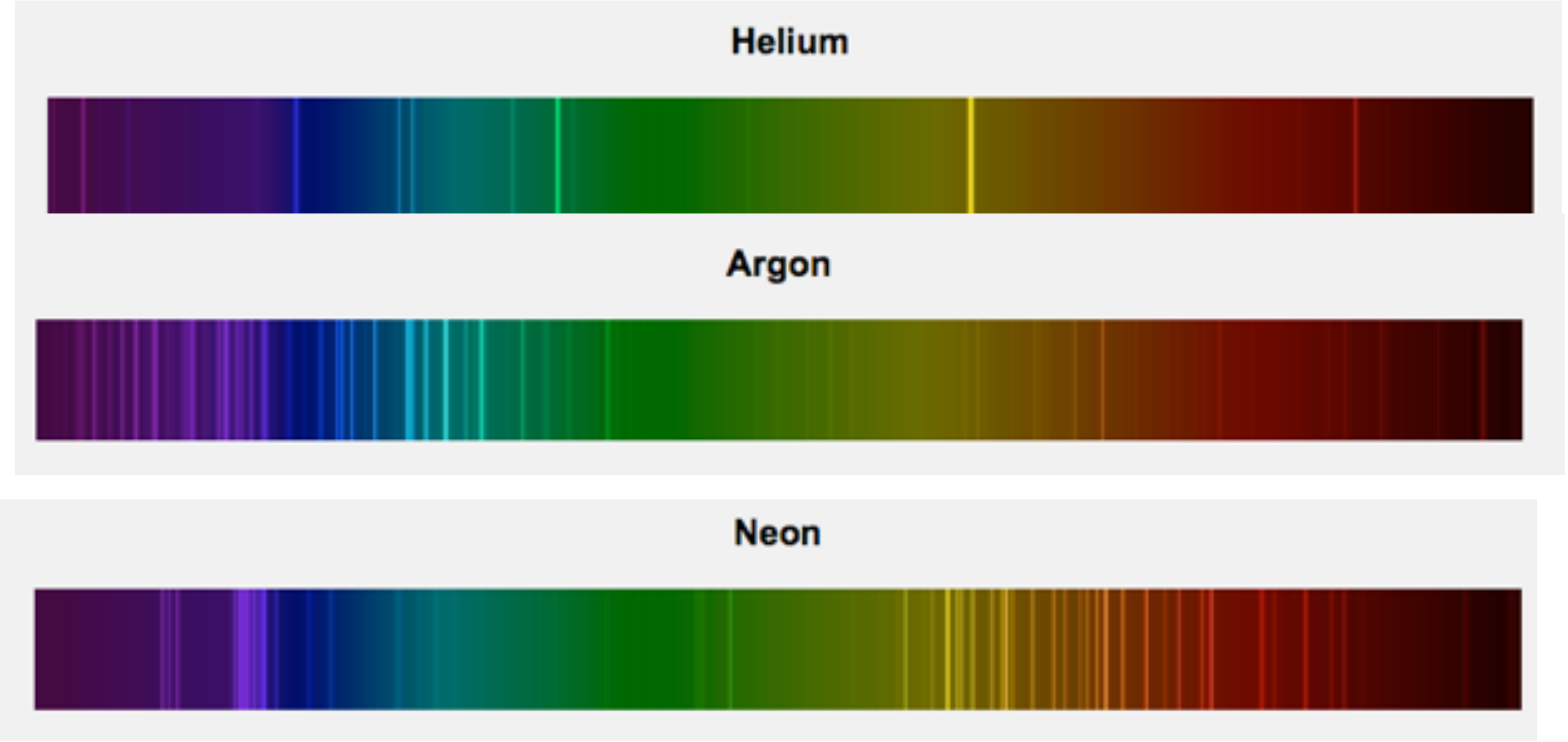
4. **Flux calibration**: Correction for throughput as a function of wavelength. Not always required.

5. **Sky subtraction**: Subtract emission lines from the sky.

6. **Object reduction**: Extracting object spectrum (``tracing'' the object) to create 1D spectrum

Reducing Spectra - Wavelength Calibration

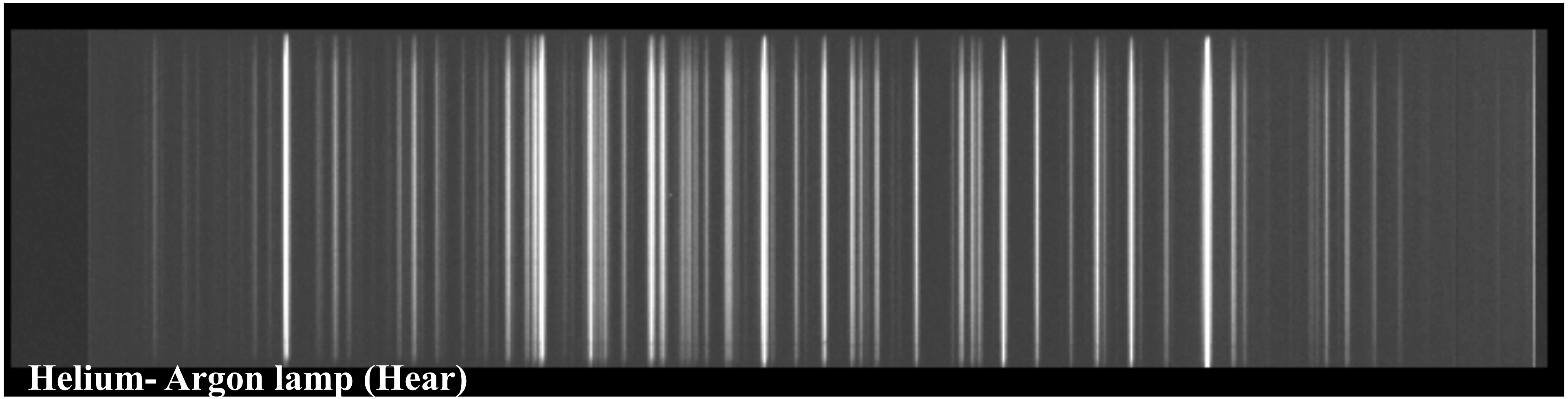
In order to determine the mapping between pixels and wavelength, we take images of a known emission line source, the same type of source as the gas-emission tubes.



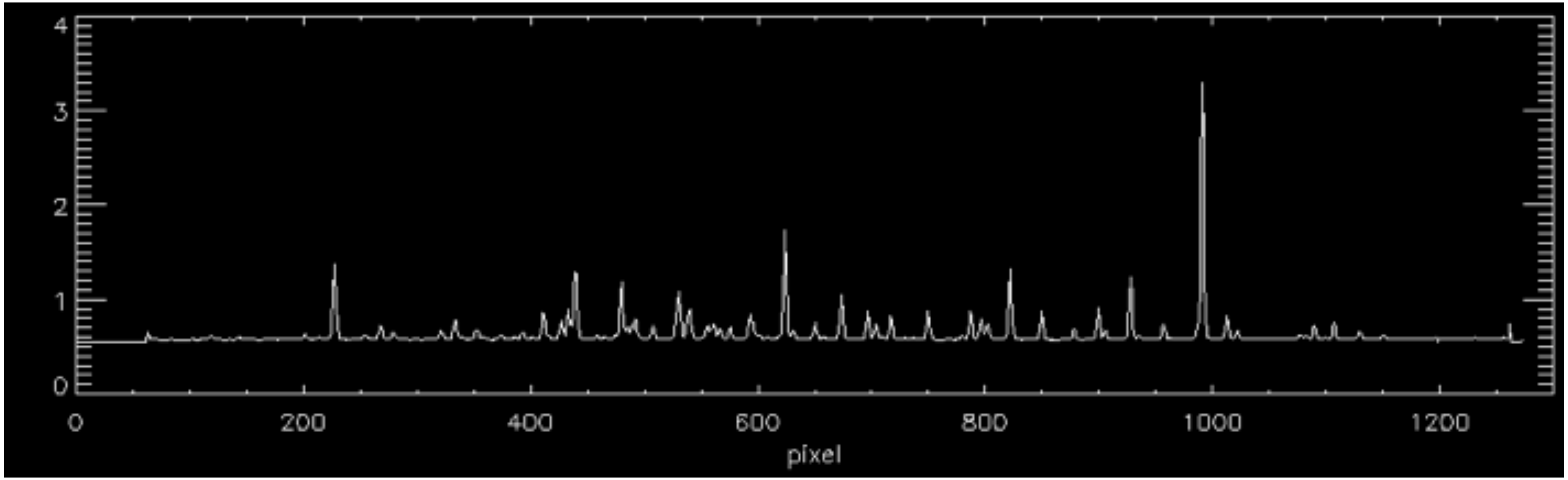
For the final project data, the calibration used Helium and Argon tubes, in part because the data are in the blue.

Reducing Spectra - Wavelength Calibration

The goal is to produce a function $\lambda = f(x,y)$ which gives λ for any pixel position on the CCD.



Need a script to collapse 2D to 1D spectrum
np.median()



Reducing Spectra - Wavelength Calibration

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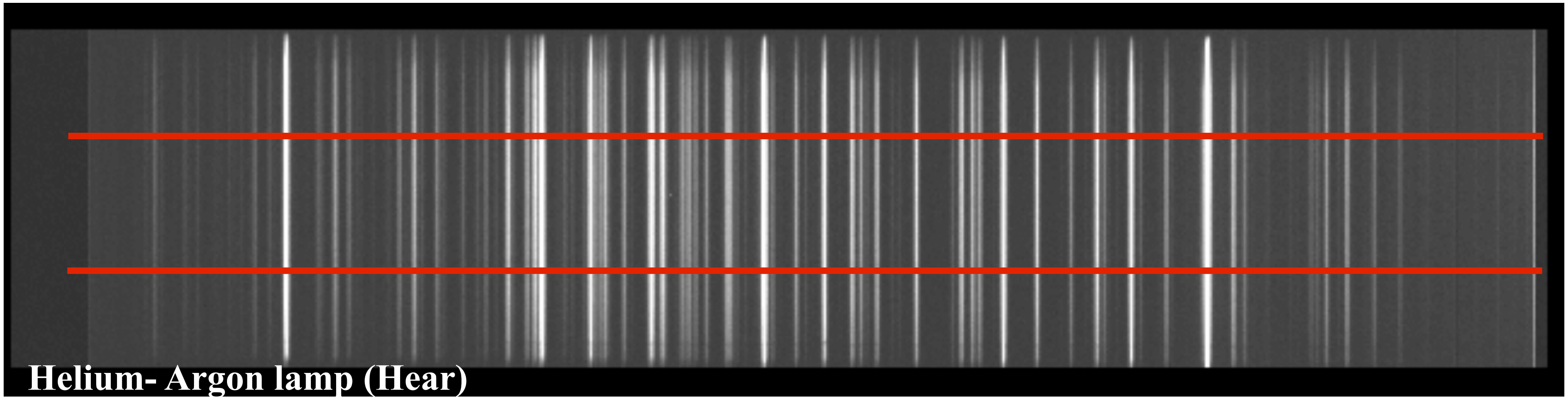

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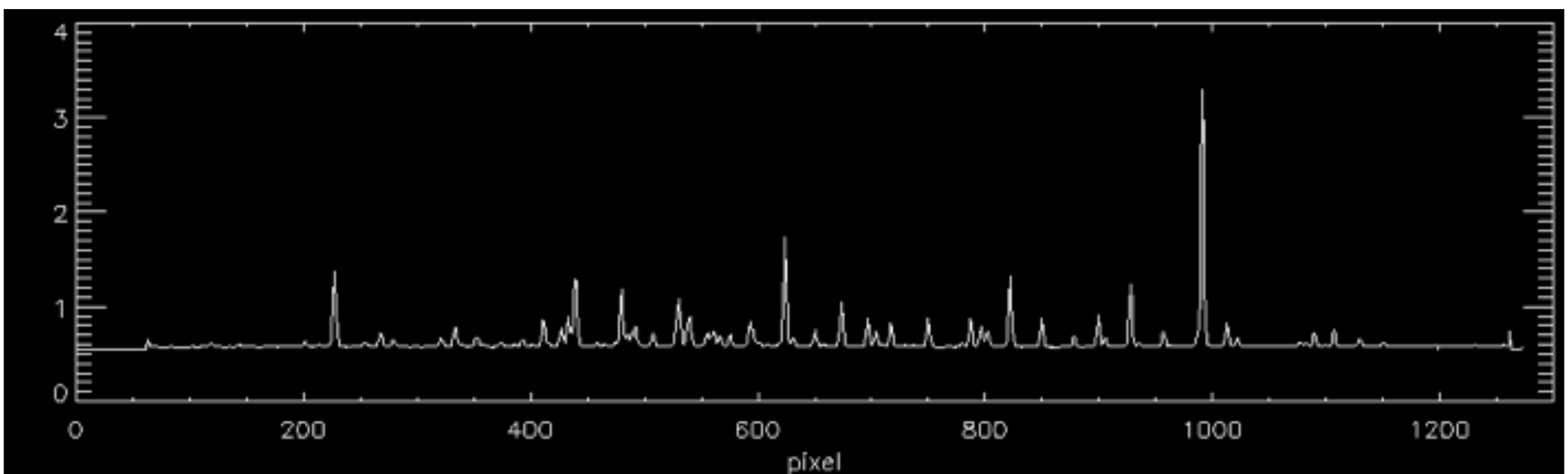
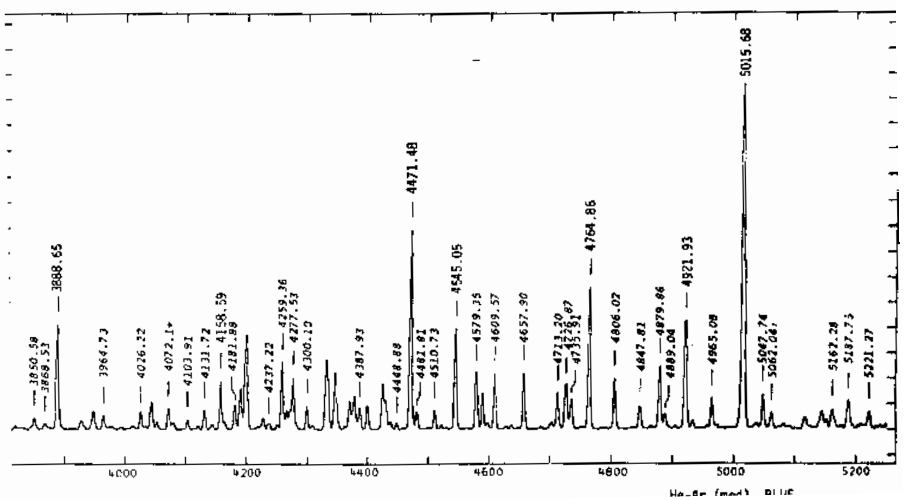
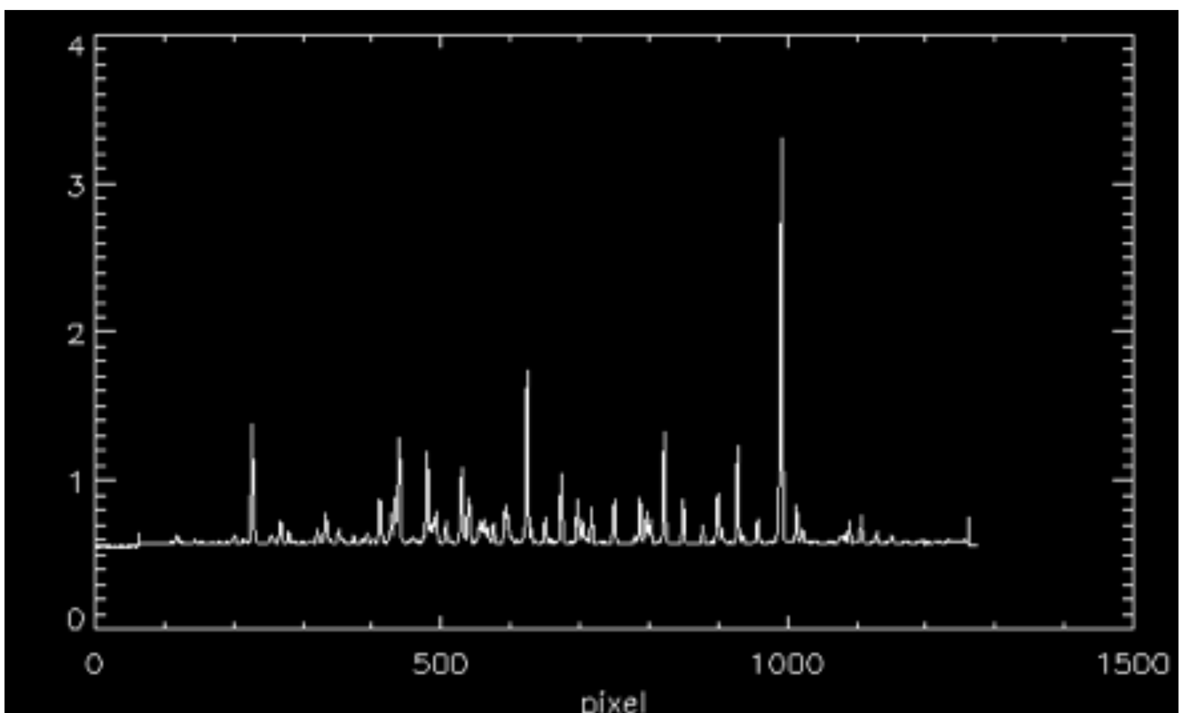
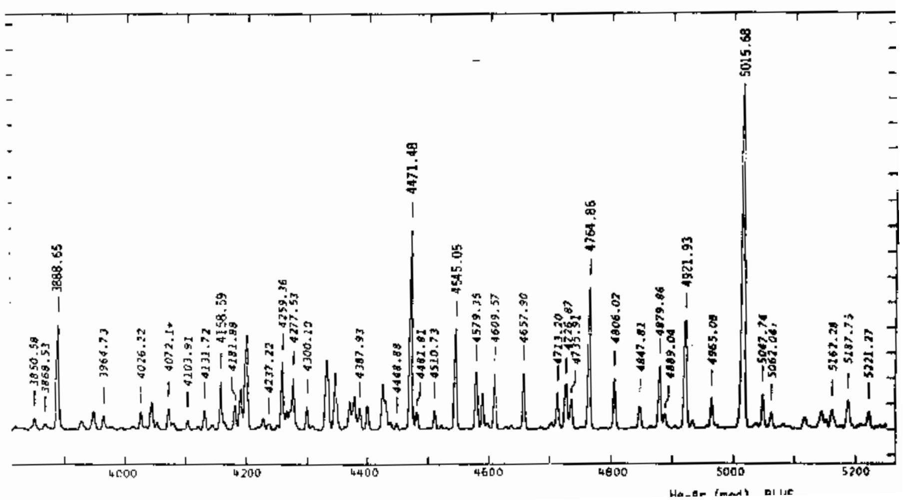


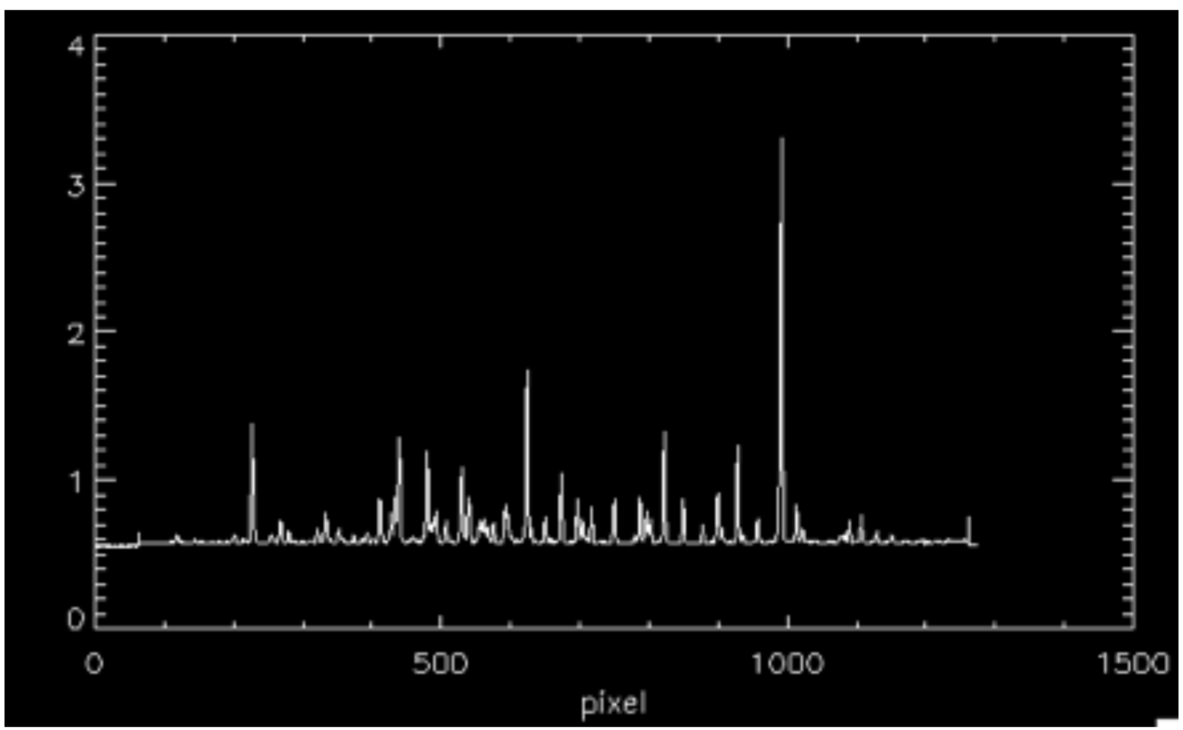
Reducing Spectra - Wavelength Calibration





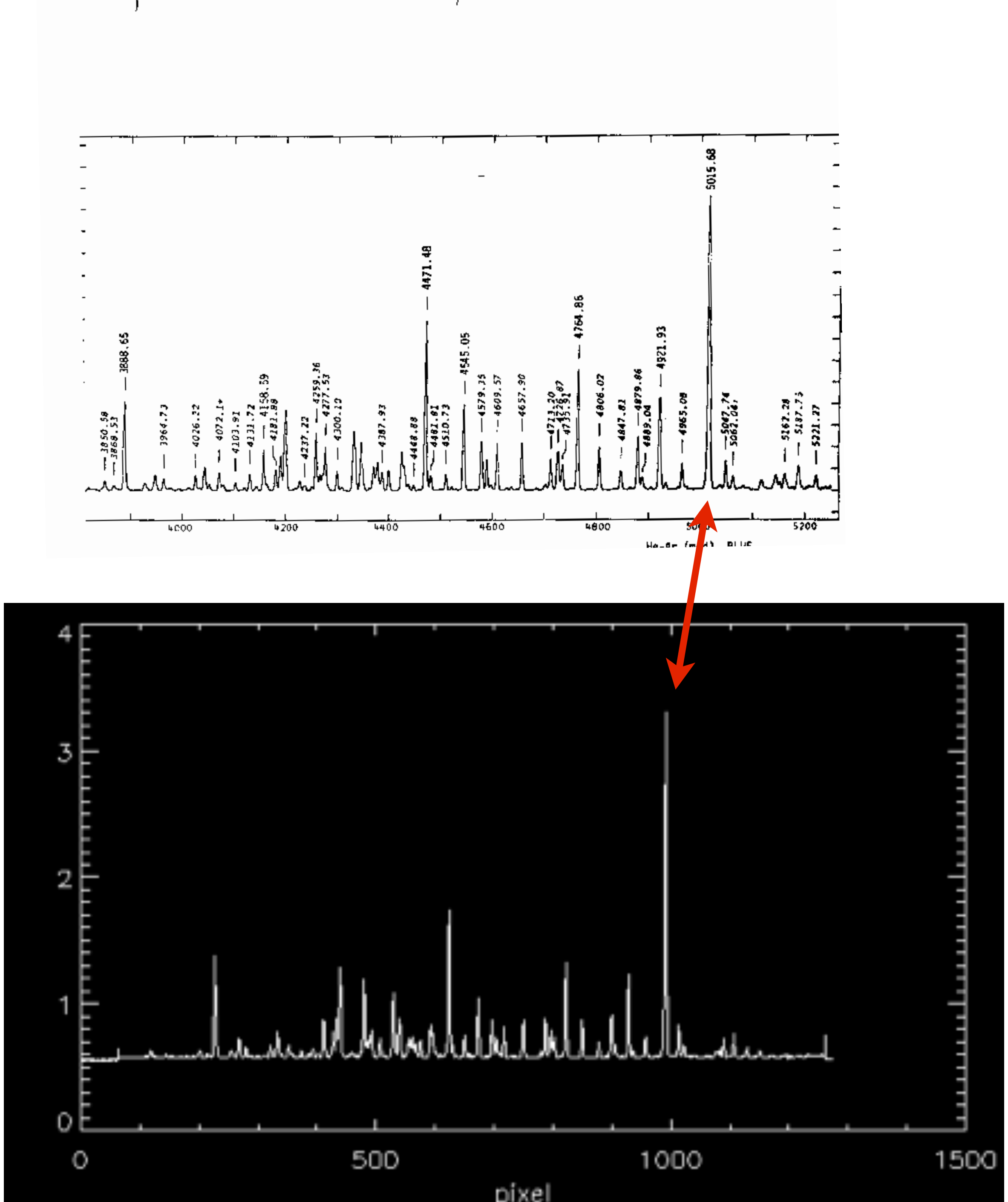
Reducing Spectra - Wavelength Calibration





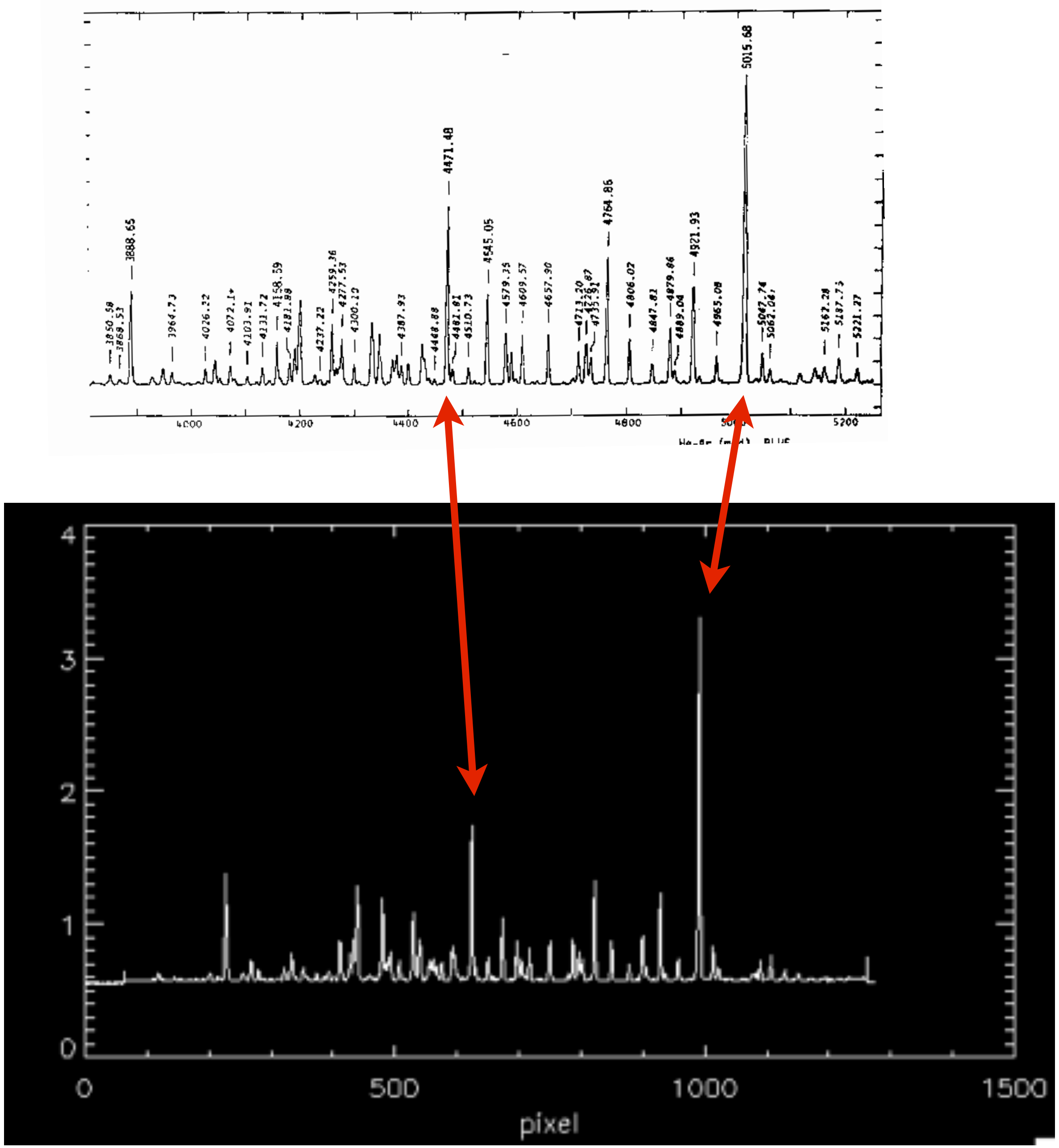
Pixel	λ

Reducing Spectra - Wavelength Calibration



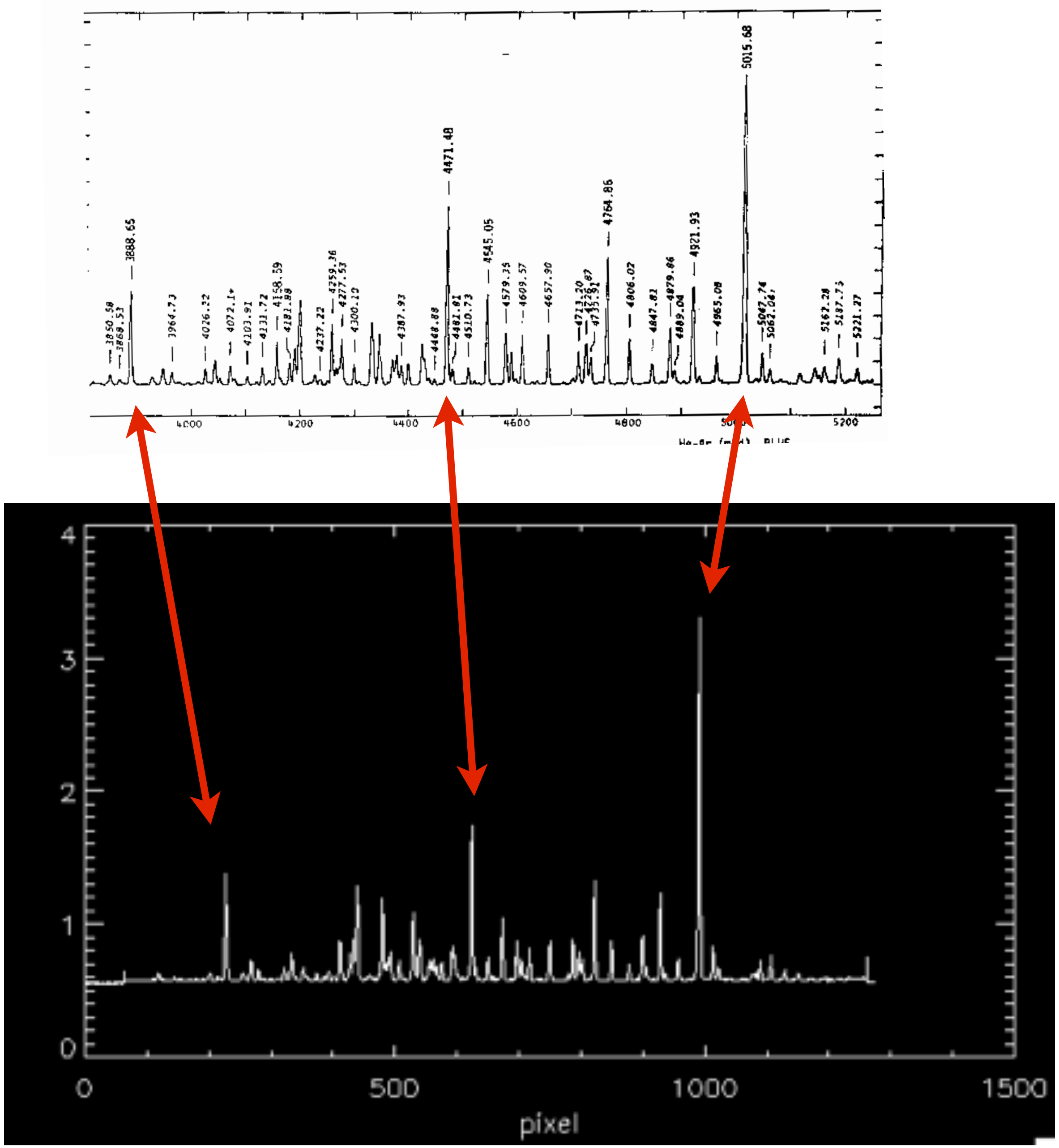
Pixel	λ
1000	5015.68

Reducing Spectra - Wavelength Calibration



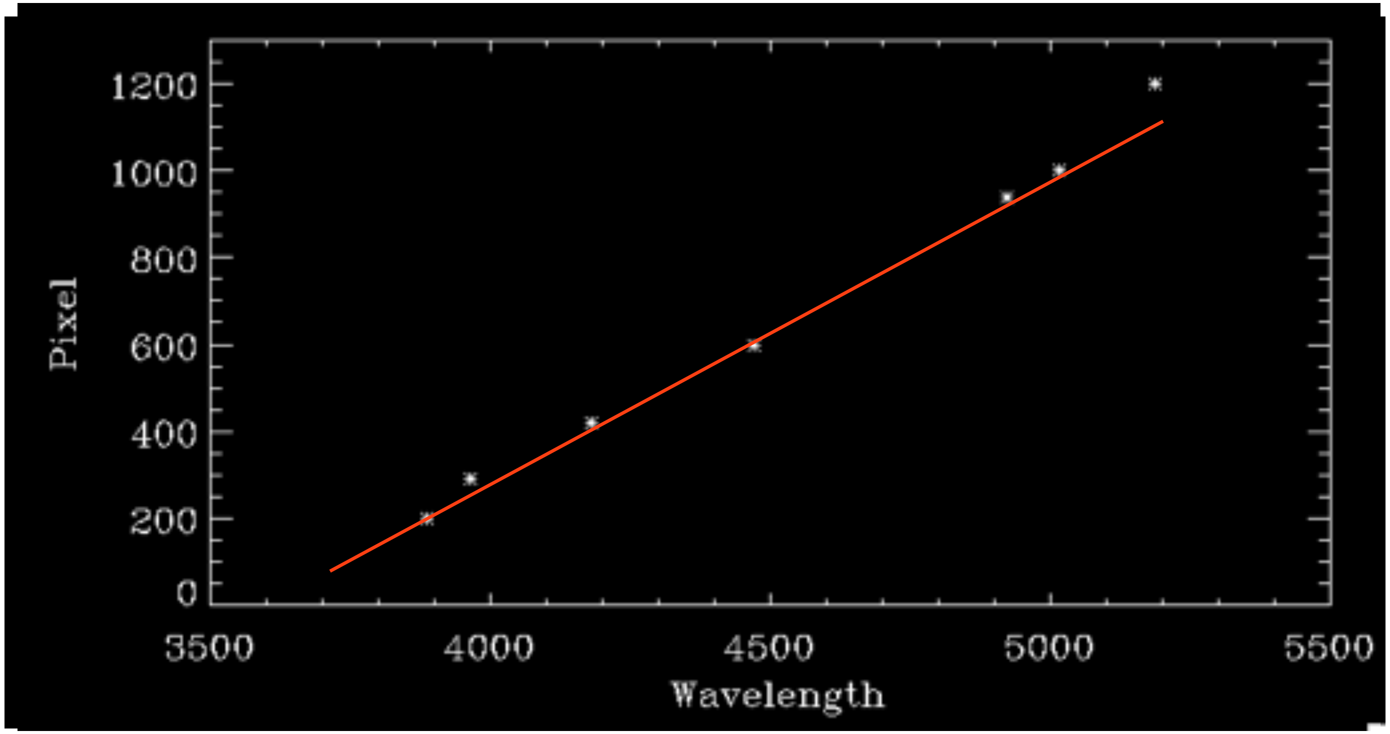
Pixel	λ
1000	5015.68
600	4471.48

Reducing Spectra - Wavelength Calibration



Pixel	λ
1000	5015.68
600	4471.48
200	3888.65

Reducing Spectra - Wavelength Calibration



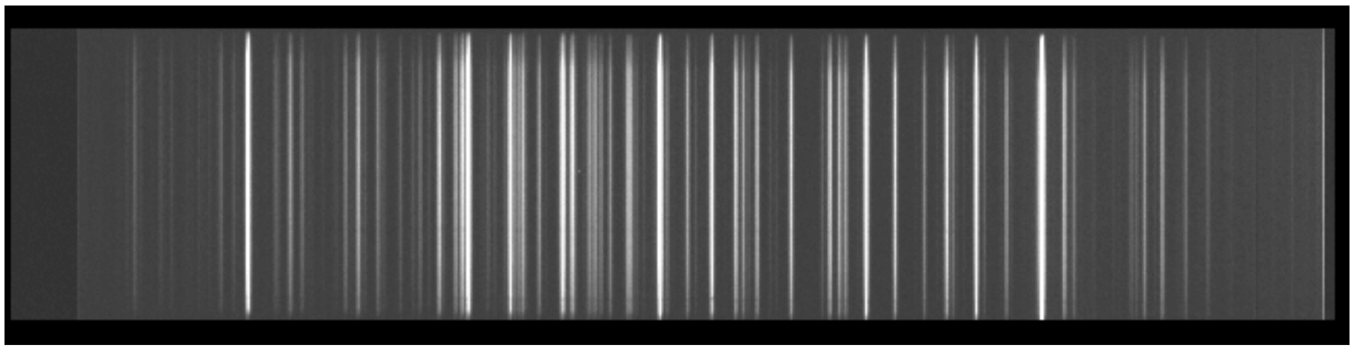
Pixel	λ
1000	5015.68
600	4471.48
200	3888.65

Wavelength Step 1: Identify arc lines using arc line list provided (minimum of 6 lines).

Wavelength Step 2: Fit function to these points (start linear, increase to a polynomial order 3-4)

Reducing Spectra - Wavelength Calibration

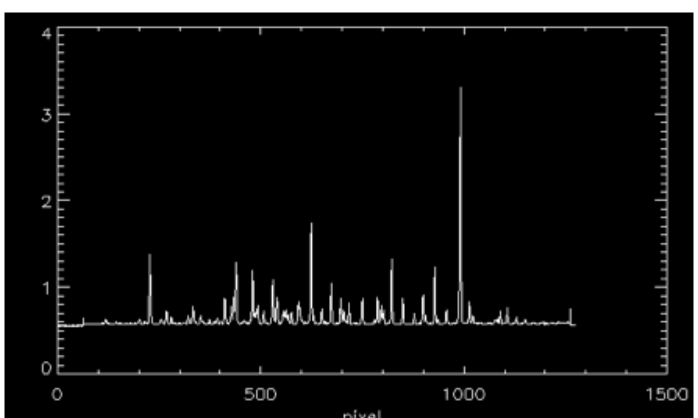
The goal is to produce a function $\lambda = f(x,y)$ which gives λ for any pixel position on the CCD.



For BH project, you can assume that wavelength is a function of x only (not y).

$$\lambda = m*x + b \qquad \text{or} \qquad \lambda = m*x^2 + n*x + b$$

Wavelength Optional Steps:



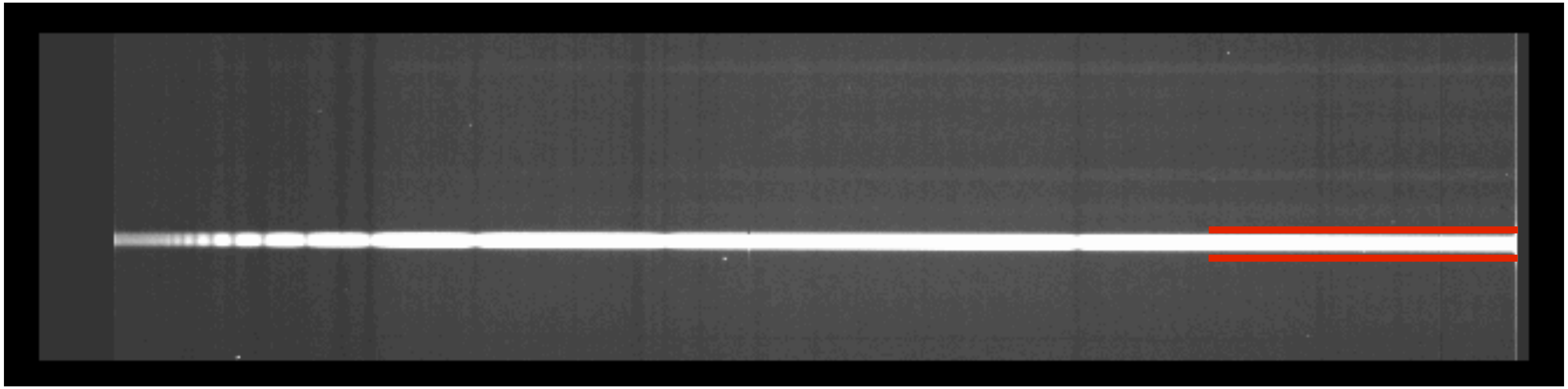
-- Rather than estimate line centers by eye, determine line center by fitting a Gaussian to each peak

-- Iterate the fit above, removing lines which deviate from overall fit.

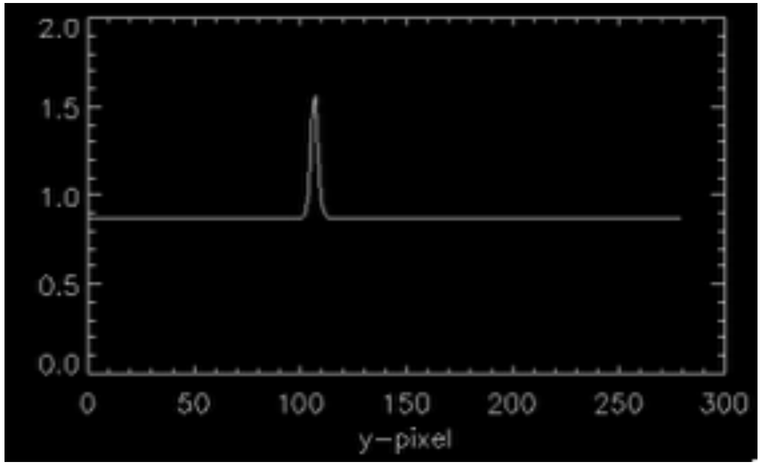
Reducing Spectra - Extract 1D Science Spectrum

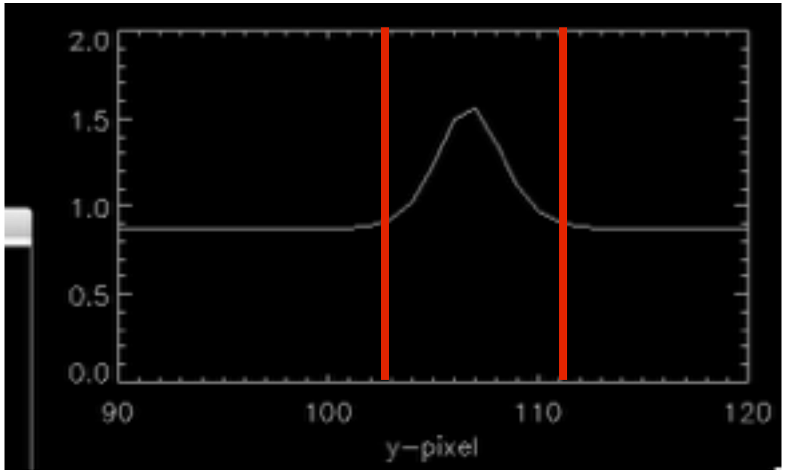
Science spectrum Step 1: Determine y-pixels covered by science target for each exposure.

Science spectrum Step 2: Extract 1D spectrum over this y-region.



To extract science spectrum and collapse to a 1D spectrum, determine y-pixels cover by science target. ** This will be different for each science spectrum **



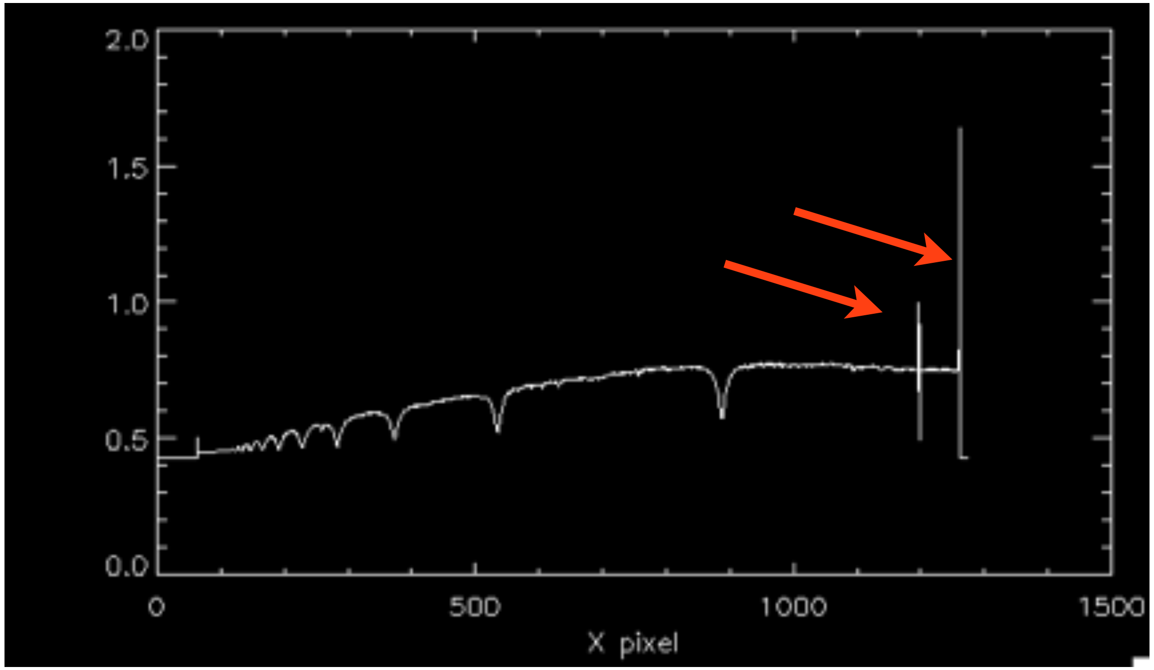


y = [103, 111]

Reducing Spectra - Extract 1D Science Spectrum

Science spectrum Step 1: Determine y-pixels covered by science target for each exposure.

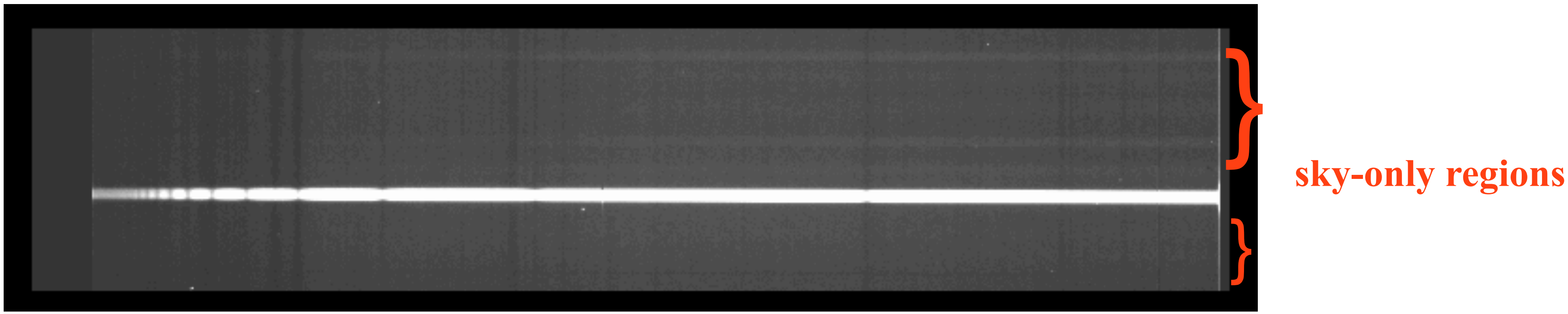
Science spectrum Step 2: Extract 1D spectrum over this y-region.



Optional Step: Fix bad pixels and bad columns.

Reducing Spectra - Sky Subtraction

The extracted 1D spectrum contains flux from the science target and flux from the sky.



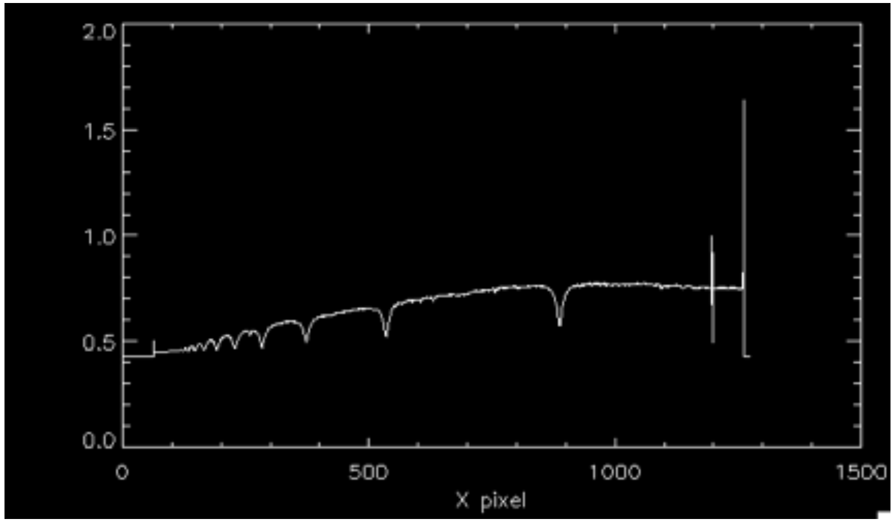
In the wavelength region covered by the BH candidate, there are no bright sky emission lines.

We do see flux from the sky, as well as a few sky *absorption* lines. For these observations, it is fine to skip the sky subtraction step.

Optional Step: plot the sky spectrum and prove that skipping this step will not affect our science results.

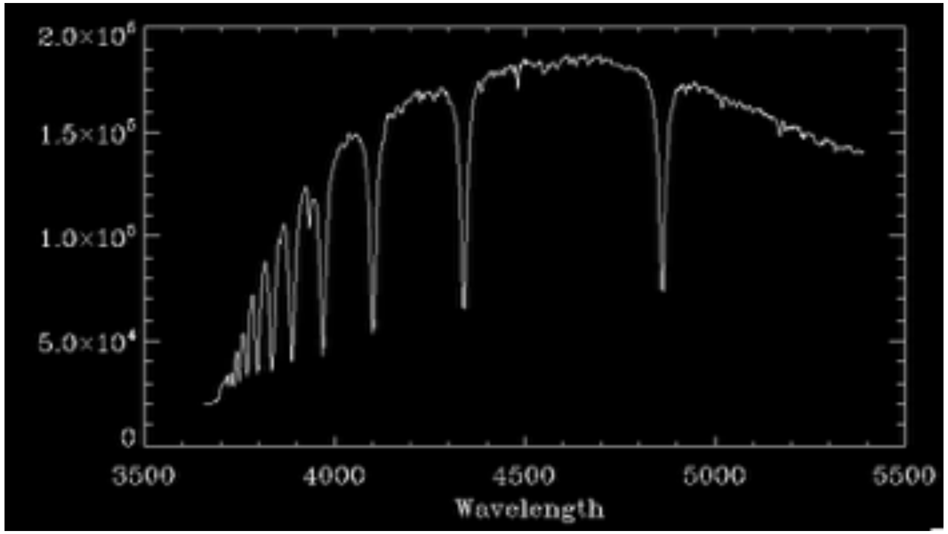
Reducing Spectra - Apply wavelength solution

The extracted 1D spectrum has x-units of CCD pixels, want to convert this wavelength.



Science spectrum Step 3: Apply wavelength solution

$$\lambda = m*x^2 + n*x + b$$



For each pixel, apply this solution to get wavelength.