Lecture 13

November 29, 2018

Lab 7

News

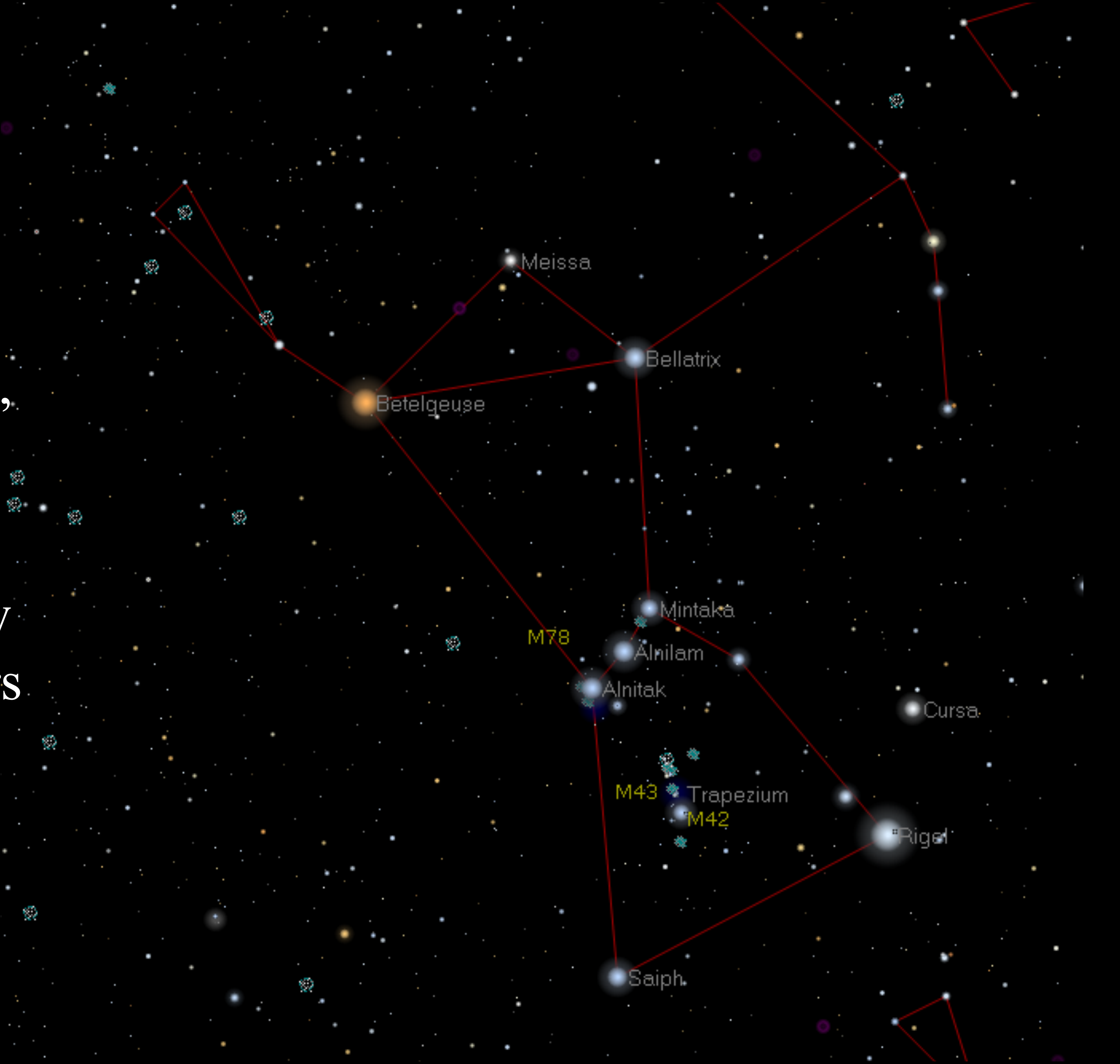
- Labs 4-6
  - At least Lab 4 handed back next week. Other labs will be available outside my door as I finish grading them.
- Lab 7: Nebular Spectroscopy
  - No observing; we will use pre-existing data.
  - Data is in /home/ph344/lab7 on the astrolab computer.
    - File names are fairly obvious, though ask if you have questions.
    - Data was taken November 18, 2014. The night was clear.
  - Lab due Wednesday, December 12.

Spectroscopy of the Emission Nebulae

- Spectroscopy is a very powerful tool for determining physical properties of astronomical objects.
  - Temperature, density, composition, …

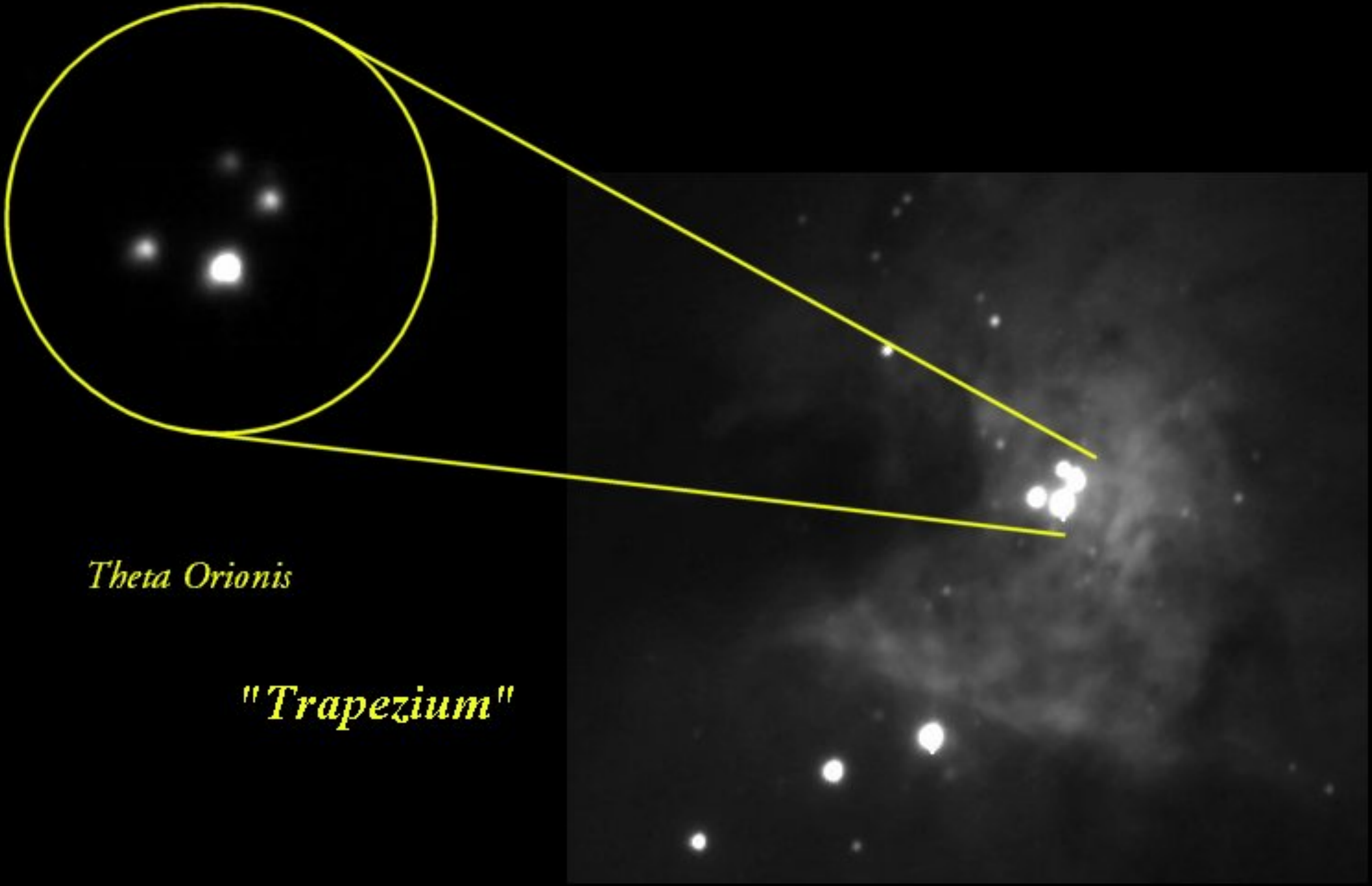
- Orion Nebula (M42)
  - Nearest site of active star formation. (~430 pc)
  - A dense cloud of (mostly) hydrogen gas illuminated and ionized by (ultraviolet) light emitted by partially embedded hot, young (newly-formed) stars.

Orion region in The Sky. The Orion Nebula (M42) is the middle “star” in the “sword” of Orion (below the three stars in the belt).



M42 (and M43) © Anglo-Australian Observatory Photo by David Malin

Near-IR (0.8 – 2.5 μm) view of the nebula taken with VISTA (Visible-IR Survey Telescope for Astronomy) at the European Southern Observ. (4.1 m aperture, 1.6 degree field of view). See deeper into the opaque regions.



The four bright stars in the middle of the cluster, the Trapezium, provide most of the UV light that formed the nebula.

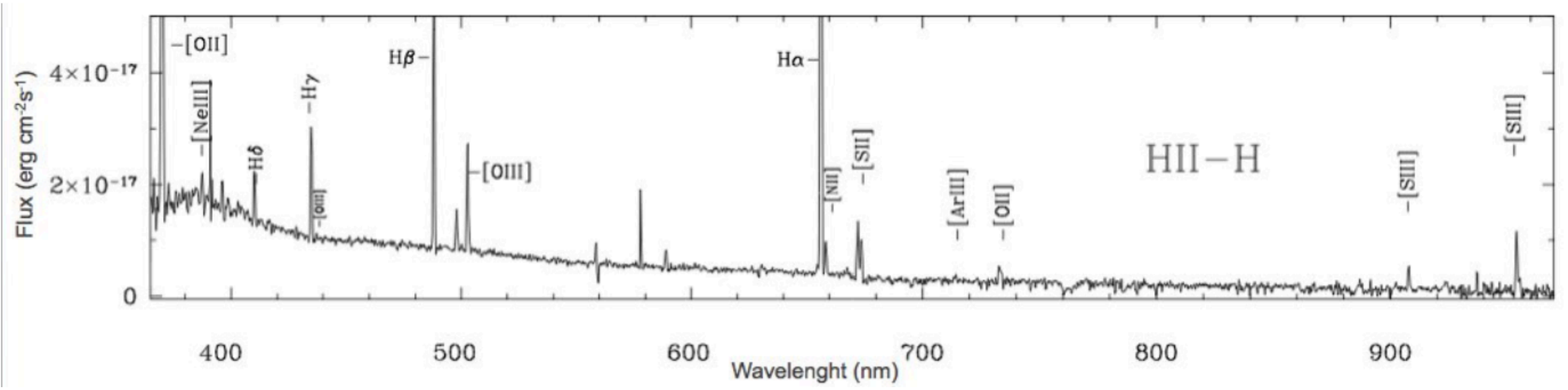
Ionized Hydrogen (HII) Regions

- Created by: HI + $\gamma_{uv} \rightarrow$ HII + e^- (ionization)
- Emission (cooling) processes:
  - Recombination: HII + $e^- \rightarrow$ HI + γ's (Balmer series)
  - Collisional excitation + radiative de-excitation: $X + e^- \rightarrow X^* + e^- \rightarrow X + \gamma + e^-$ (emission lines)
  - Free-free emission (continuum radio emission)

- Physical conditions:
  - $T \approx 10^3 - 10^4$ K
  - $n_e \approx$ 100's – 1000's cm^{-3} (depending on the nebula)

Ionized Hydrogen (HII) Regions

- The emission processes produce a spectrum like that below.
  - VLT spectrum of HII region in galaxy Sextans B.



M. A. Rodrigues 2010 arXiv:1011.1884v2

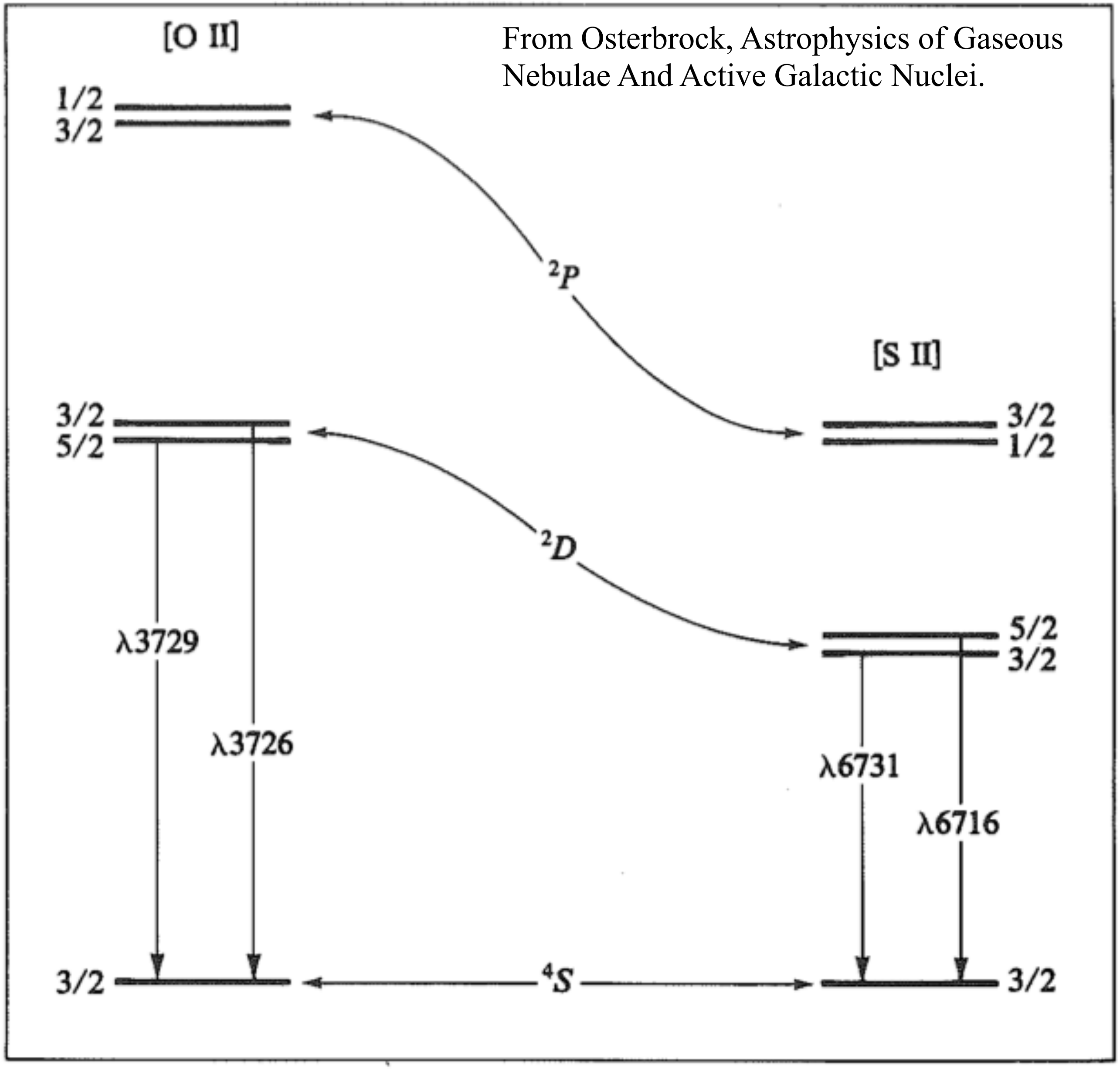
- Relative strengths of emission lines yield (average) density and temperature of the gas.

Measuring Electron Density, N_e

- Use the effects of collisional de-excitation on atomic level populations.
  - Level populations are found by comparing line ratios for two transitions from a single ion.
- Choose lines arising from a two levels with nearly the same excitation energy.
  - Relative excitation rates then depend only on collisional cross-sections, not temperature.
  - If the two levels have different radiative transition probabilities or different collisional de-excitation rates, then the line ratio depends on density.
  - The two useful ions are OII and SII.

Ground state and first excited states of singly ionized oxygen and sulfur. These have the same number of electrons in the outer-most shell (n=2 shell for O and n=3 for S): 3 electrons in the p-state, i.e., electron orbital angular momentum = 1. So the energy levels have a similar structure.

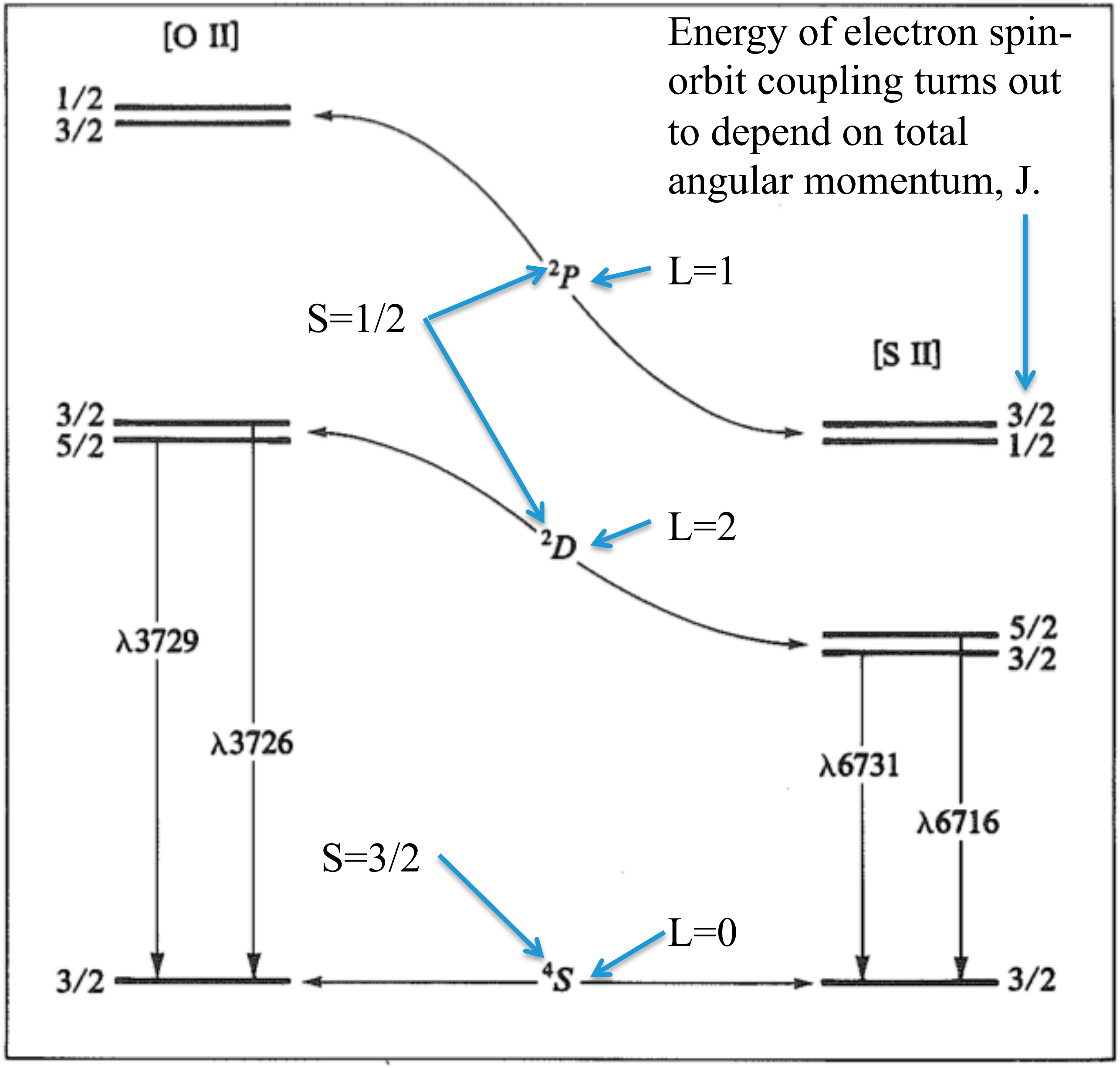
Note the closely-spaced pair of first excited states. We use [SII] instead of [OII], despite the much larger abundance of oxygen, because our CCD is much more sensitive at 6700 Å than at 3700 Å.



From Osterbrock, Astrophysics of Gaseous Nebulae And Active Galactic Nuclei.

FIGURE 5.2
Energy-level diagrams of the $2p^3$ ground configuration of [O II] and $3p^3$ ground configuration of [S II].

An aside:
Calculating these states is complex. It is a useful approximation that the overall wavefunction of the 3 electrons can be characterized by the total orbital angular momentum (L) and spin (S). The allowed combinations of L and S are constrained by the Pauli exclusion principle. States of larger total S tend to have lower energy (electrons are further apart if spins aligned because of Pauli exclusion). For a fixed S, states of larger L also tend to have lower energy (electrons again tend to be further apart).



Energy of electron spin-orbit coupling turns out to depend on total angular momentum, J.

FIGURE 5.2
Energy-level diagrams of the $2p^3$ ground configuration of [O II] and $3p^3$ ground configuration of [S II].

Measuring Electron Density, N_e

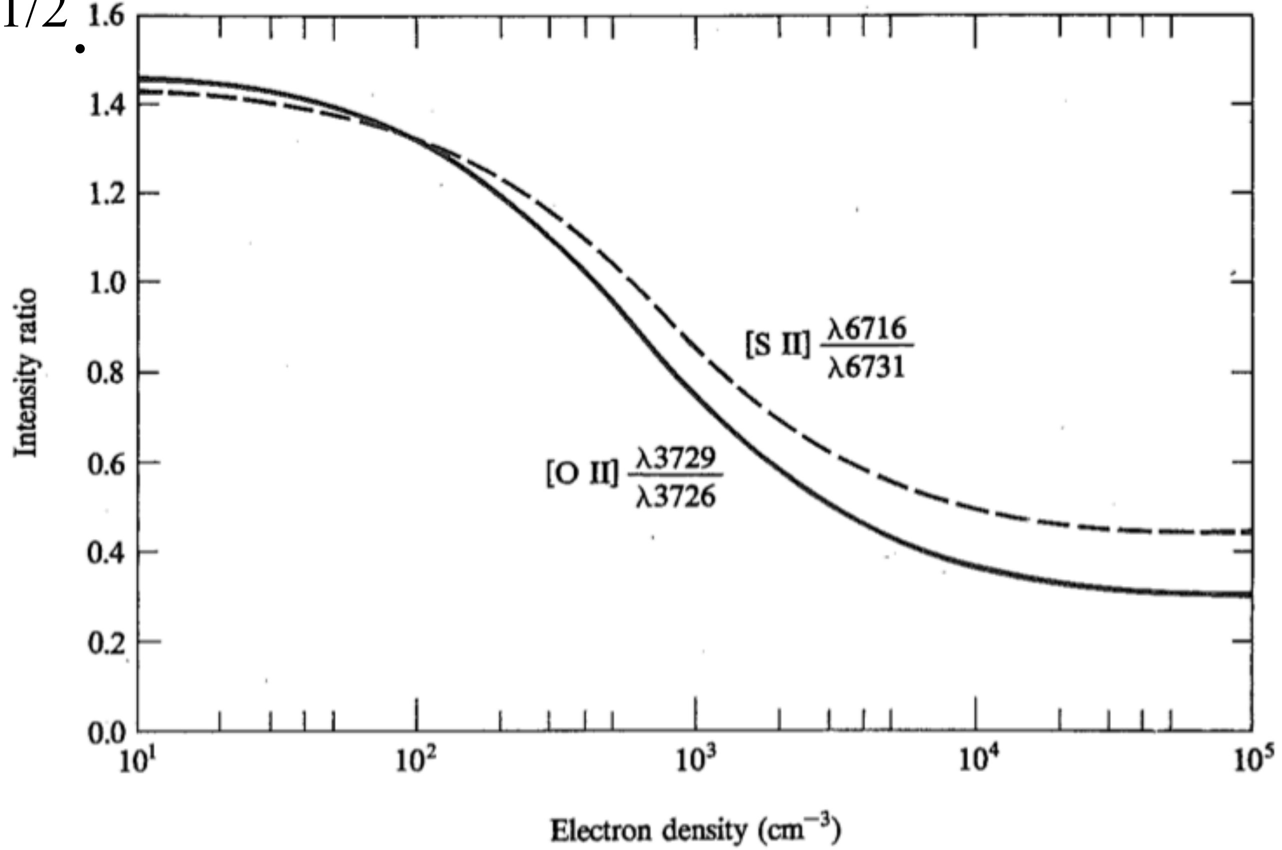
- In the limit $N_e \rightarrow 0$, each collisional excitation is followed by the emission of a photon (rather than a collisional de-excitation).
  - Relative rates of collisional excitation turn out to depend on just the statistical weights of the two levels, and the ratio of line strengths is 3/2.
- In the limit of high N_e, the level populations are determined by thermal equilibrium and again their ratio is the ratio statistical weights.
  - The line ratio is then the ratio of weights multiplied by the ratio of radiative transition probabilities, which product turns out to be ≈ 0.4.

Measuring Electron Density, N_e

- The transition between the two limits occurs when the collisional de-excitation rate is about equal to the radiative rates.
  - These [OII] and [SII] line pairs are useful because the transition occurs at densities around those found in HII regions.
  - The collision rate per ion is $\propto N_e / v_e \propto N_e / T_e^{1/2}$, where v_e and T_e are the electron velocity and temperature. So the transition does depend some on temperature.
  - The figure in the next slide (and the lab) comes from detailed calculations of the rates into and out of the states as a function of N_e and T_e.

Measuring Electron Density, N_e

- The x-axis of the figure should be interpreted as $N_e(10^4\ \mathrm{K}/T)^{1/2}$.



From Osterbrock, Astrophysics of Gaseous Nebulae And Active Galactic Nuclei.

FIGURE 5.3
Calculated variation of [O II] (*solid line*) and [S II] (*dashed line*) intensity ratios as function of N_e at $T = 10,000°$ K. At other temperatures the plotted curves are very nearly correct if the horizontal scale is taken to be $N_e(10^4/T)^{1/2}$.

Measuring Electron Temperature, T_e

- Some ions have two excited states with significantly different energies and that both produce emission lines at observable λ’s.
  - The rate of collisional excitation into the two levels will depend strongly on temperature, as will the relative strength of the emission lines.
  - The ratio of excitation rates is the ratio of the collisional cross-sections, which just depends on atomic physics, times the Boltzmann factor for the energy difference between the two states, ΔE:

$$e^{\Delta E/kT}$$

Ground state and first excited states of doubly ionized oxygen and singly ionized nitrogen. These have the same number of electrons in the outer-most shell (n=2 shell): 2 electrons in the p-state, i.e., electron orbital angular momentum = 1. So the energy levels have a similar structure.

Note the wide separation of the first two excited states, which makes their relative populations dependent on T. Also note that transitions from both levels produce observable lines.

We use [NII] instead of [OIII] because our CCD is not very sensitive at 4363 Å.

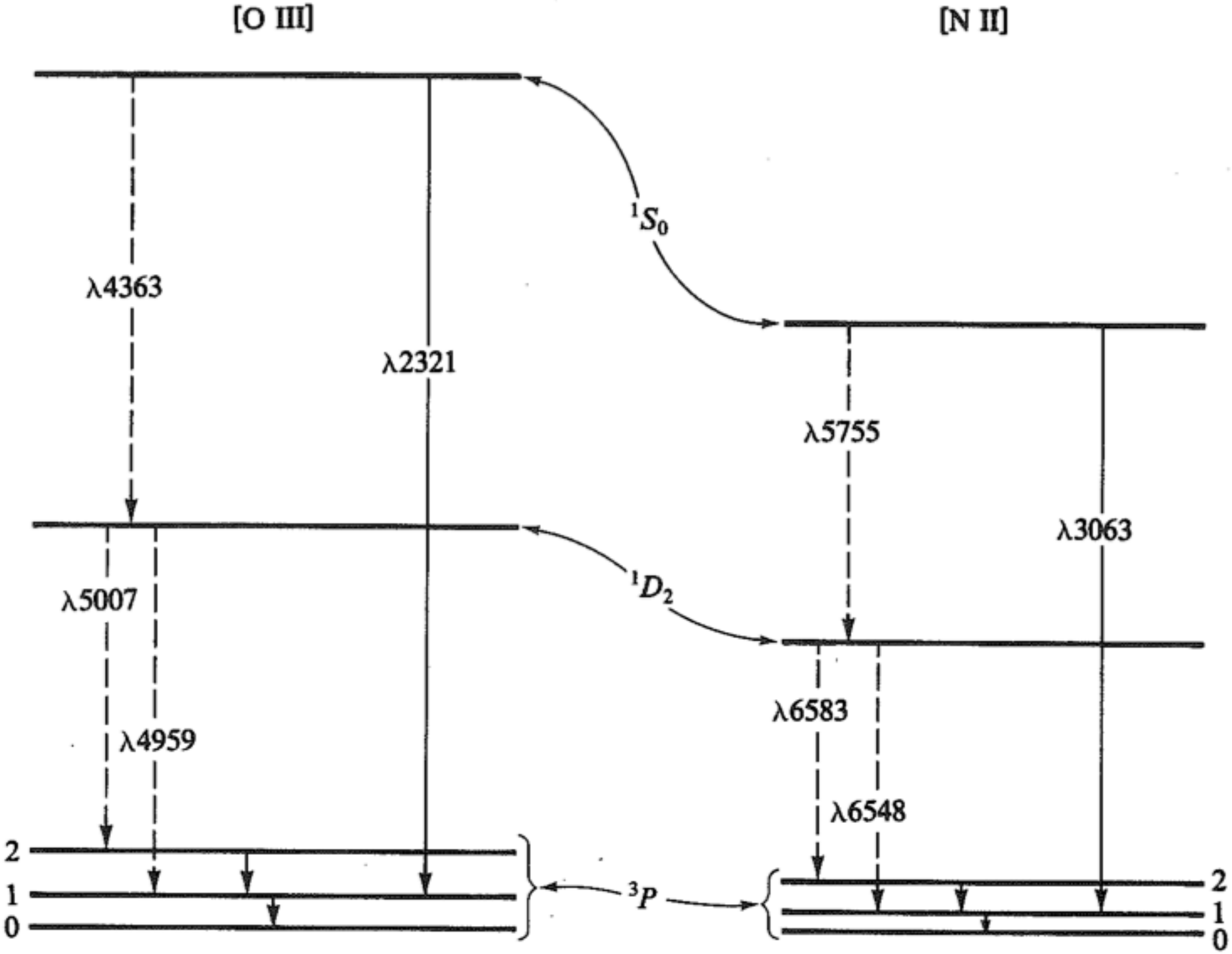


FIGURE 3.1
Energy-level diagram for lowest terms of [O III], all from ground $2p^2$ configuration, and for [N II], of the same isoelectronic sequence. Splitting of the ground ^3P term has been exaggerated for clarity. Emission lines in the optical region are indicated by dashed lines, and by solid lines in the infrared and ultraviolet. Only the strongest transitions are indicated.

Measuring Electron Temperature, T_e

- In the low-density limit, every collisional excitation of [NII] is followed by
  - Emission of a 6583 Å or a 6548 Å photon for the ^1D state, with the ratio of fluxes given by the ratio of the transition probabilities.
  - Emission of a 5755 Å or a 3063 Å photon for the ^1S state, with the ratio again given by the transition probabilities. Only the 5755 Å photon is observable. Each 5755 Å transition also produces an additional 6583 Å or a 6548 Å photon.

Measuring Electron Temperature, T_e

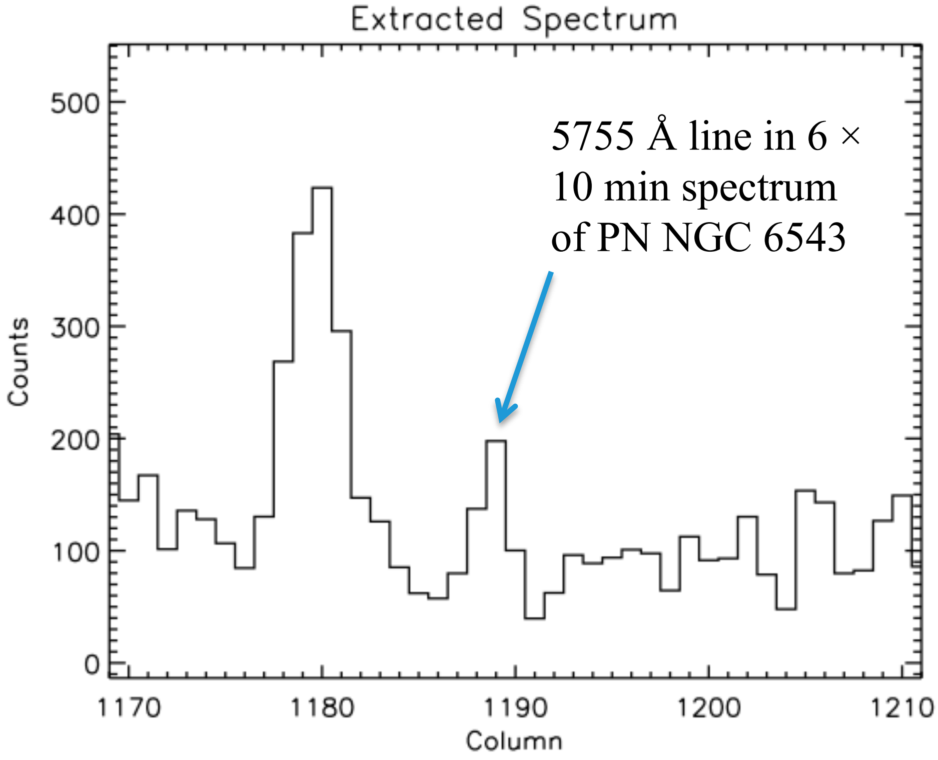
- At high densities must take collisional excitation from the 1st to the 2nd excited state into account, as well as collisional de-excitation.
  - Is usually not very important for HII regions.
- Detailed calculations give the result:

$$\frac{j_{\lambda 6548} + j_{\lambda 6583}}{j_{\lambda 5755}} = \frac{6.91 \exp[(2.50 \times 10^4 K)/T]}{1 + (2.5 \times 10^{-5} cm^3) N_e (10^4 K/T)^{1/2}}$$

  - The denominator of the rhs of the equation corrects for collisional effects at high densities.
  - Should correct the ratio for differential extinction. We ignore this since the λ's are not too different.

Measuring Electron Temperature, T_e

- The largest observational difficulty is that the 5755 Å line is weak and hard to measure accurately. The 6548 Å and 6583 Å lines are strong.



5755 Å line in 6 × 10 min spectrum of PN NGC 6543

- Should correct the observed flux ratio for differential extinction. We ignore this since the wavelengths are not too different.

Measuring Dust Extinction

- Calculations of ionization equilibrium show that the ratio of the intensities of the Balmer lines are relatively insensitive to temperature and density.

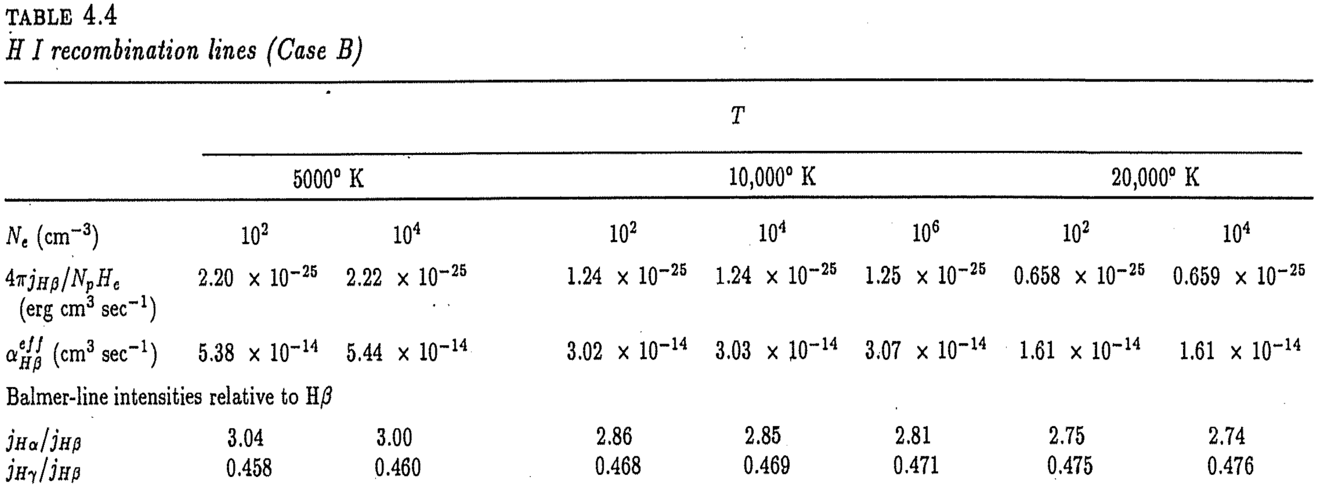


TABLE 4.4
H I recombination lines (Case B)

	T						
	5000° K		10,000° K			20,000° K	
N_e (cm^{-3})	10^2	10^4	10^2	10^4	10^6	10^2	10^4
$4\pi j_{H\beta}/N_pH_e$ (erg cm^3 sec^{-1})	2.20×10^{-25}	2.22×10^{-25}	1.24×10^{-25}	1.24×10^{-25}	1.25×10^{-25}	0.658×10^{-25}	0.659×10^{-25}
$\alpha_{H\beta}^{eff}$ (cm^3 sec^{-1})	5.38×10^{-14}	5.44×10^{-14}	3.02×10^{-14}	3.03×10^{-14}	3.07×10^{-14}	1.61×10^{-14}	1.61×10^{-14}
Balmer-line intensities relative to Hβ							
$j_{H\alpha}/j_{H\beta}$	3.04	3.00	2.86	2.85	2.81	2.75	2.74
$j_{H\gamma}/j_{H\beta}$	0.458	0.460	0.468	0.469	0.471	0.475	0.476

- Extinction causes:

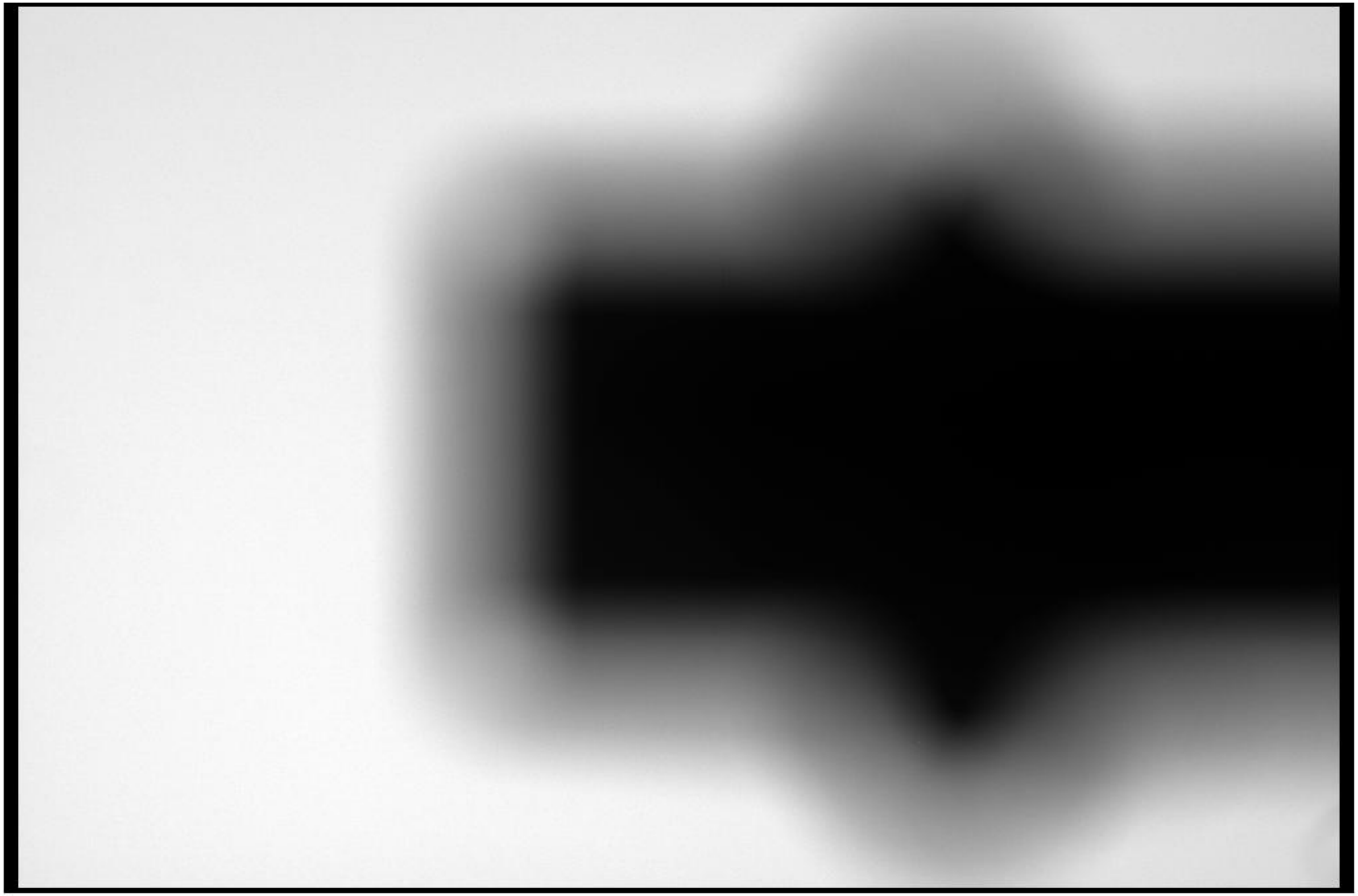
$$\frac{j_{H\alpha}}{j_{H\beta}} = \frac{j_{o,H\alpha}}{j_{o,H\beta}} e^{-(\tau_{H\alpha}-\tau_{H\beta})} = \frac{j_{o,H\alpha}}{j_{o,H\beta}} 10^{-0.434(\tau_{H\alpha}-\tau_{H\beta})} = \frac{j_{o,H\alpha}}{j_{o,H\beta}} 10^{0.35c}$$

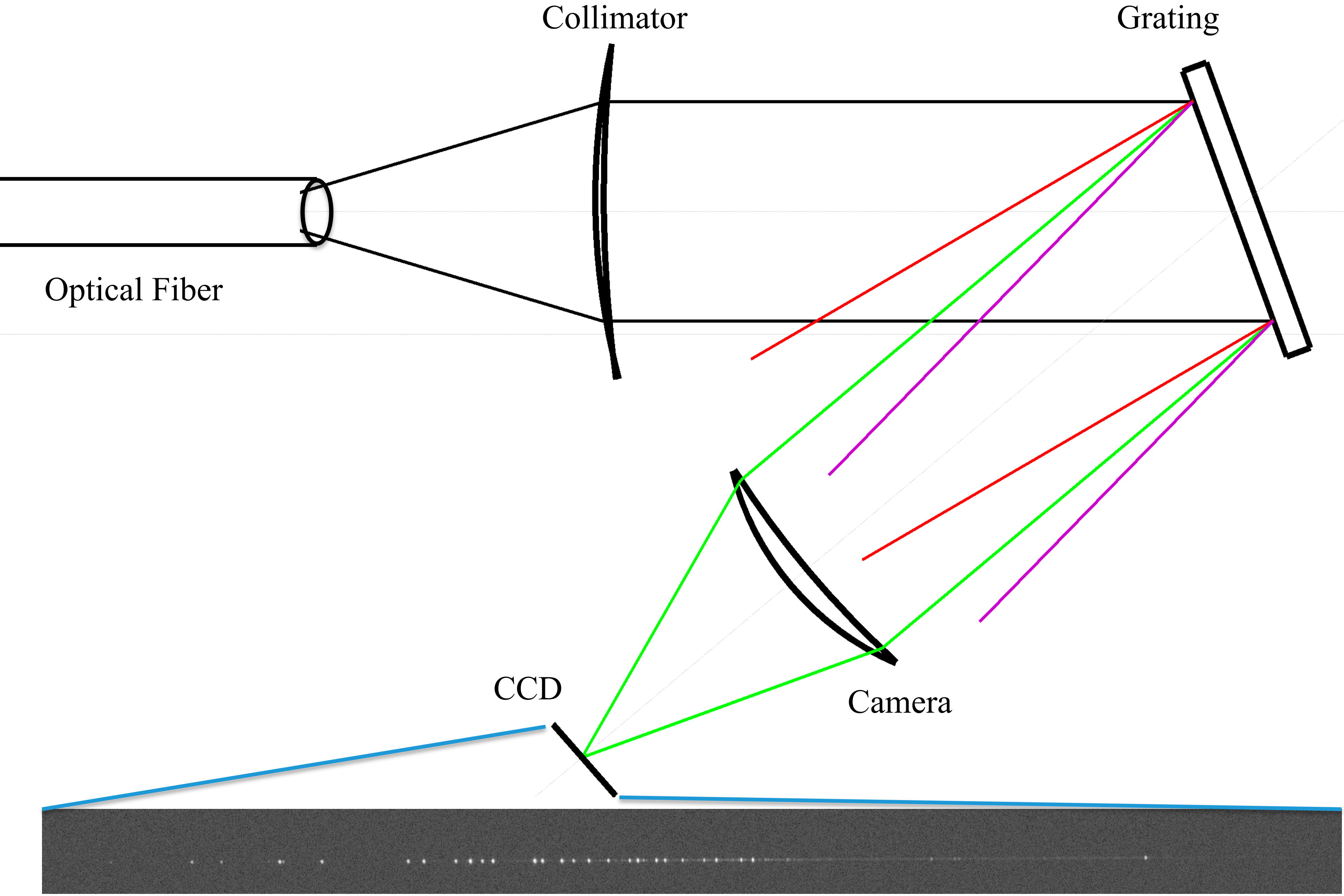
Here $\tau_{H\alpha} - \tau_{H\beta} = -0.35C$, where C is a measure of the amount of extinction and the coefficient comes from the measured dependence of extinction on wavelength. The quantity $c = 0.434C$ is a standard measure of the extinction.

Spectrograph

- An optical fiber takes light from the focal plane of the telescope to the entrance aperture of the spectrograph.
  - 5 arcsec diameter on sky (~5 CCD pixels, 2×2)
- Moving in a mirror directs light from part of the CCD field to the fiber.
  - Fiber is at (1140,690) in 2×2 binned image of main camera.
- A grating in the spectrograph disperses the light from the fiber into a spectrum which is recorded by a second CCD.

Shadow of pick-off mirror on main CCD field of view.





Schematic design of the spectrograph.

Operational Challenges

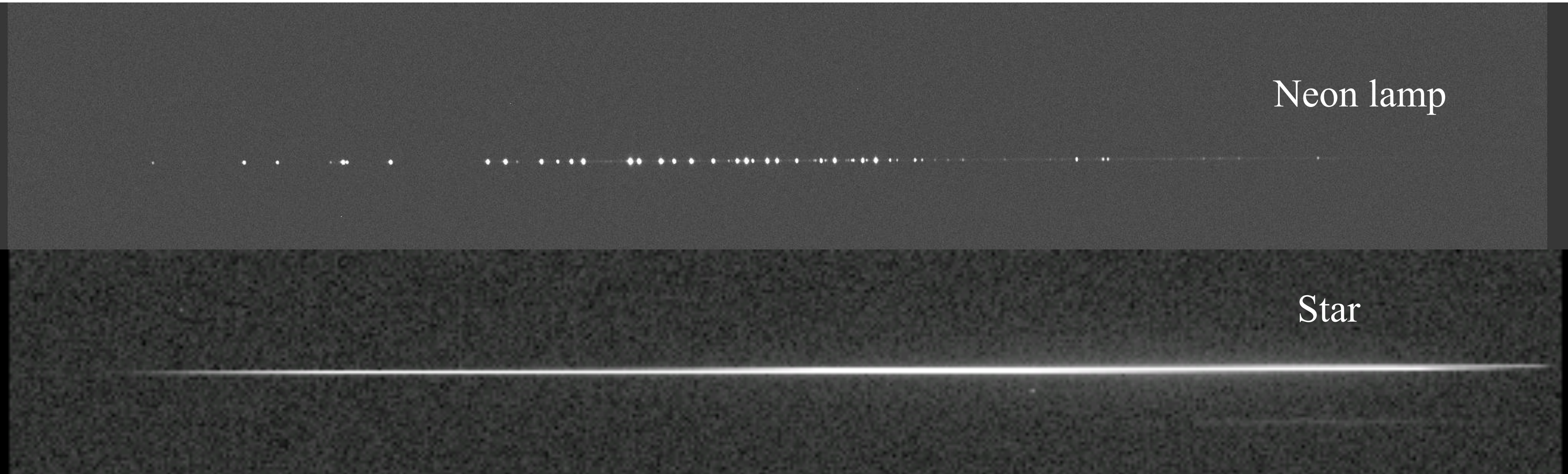
- Using two CCDs simultaneously.
  - Turn on imaging CCD and then start imager CCDSoft.
  - Next turn on the spectroscopic CCD (under the table) and start the spectrograph CCDSoft.
- Getting the object on the fiber.
  - Use the main imager and motion controls to put the object at the correct (x,y).

Observing Sequence

- Take spectra of a neon emission-line lamp.
  - Used for wavelength calibration.
- Take spectrum the spectrophotometric standards (Epsilon Orionis).
  - Used to calibrate sensitivity as a function of wavelength using known flux *vs.* wavelength.
- Take spectrum of bright part of the Orion Nebula (avoiding stars).

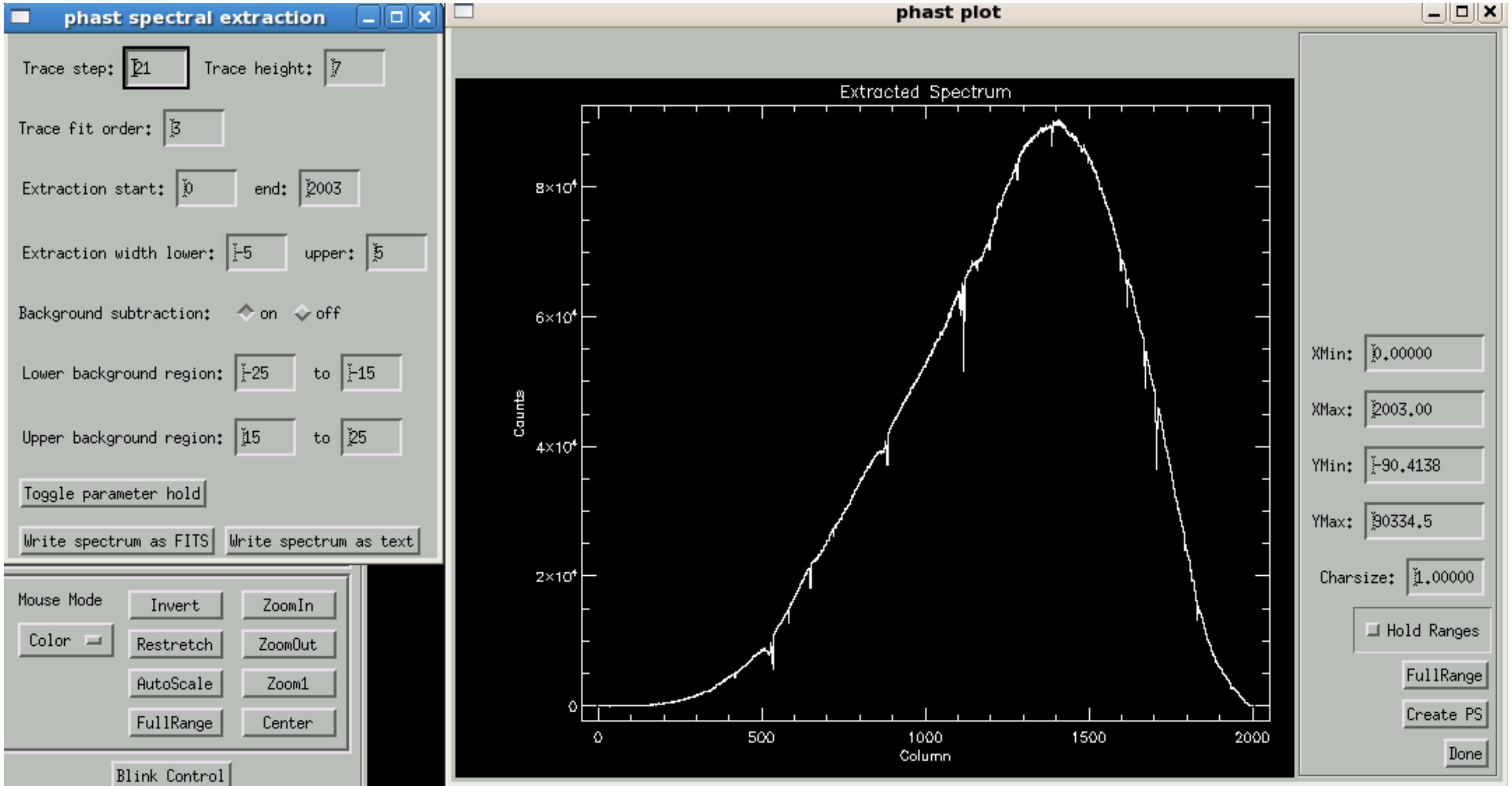
Processing Spectra

- Subtract dark (if not auto-subtracted)
- Extract 1-D spectrum from 2-D image
- Determine wavelength as a function of column #
  - Fit: λ = polynomial(x) using (x,λ) pairs determined by emission lines in the spectrum of a neon lamp.



Processing Spectra

- In ruphast, the x key will “trace” the spectrum in the 2-D image, extract a 1-D spectrum (counts *vs*. x position, and plot it. Can save as FITS file.



phast spectral extraction

Trace step: 21 Trace height: 7

Trace fit order: 3

Extraction start: 0 end: 2003

Extraction width lower: -5 upper: 5

Background subtraction: ◇ on ◇ off

Lower background region: -25 to -15

Upper background region: 15 to 25

phast plot

XMin: 0.00000

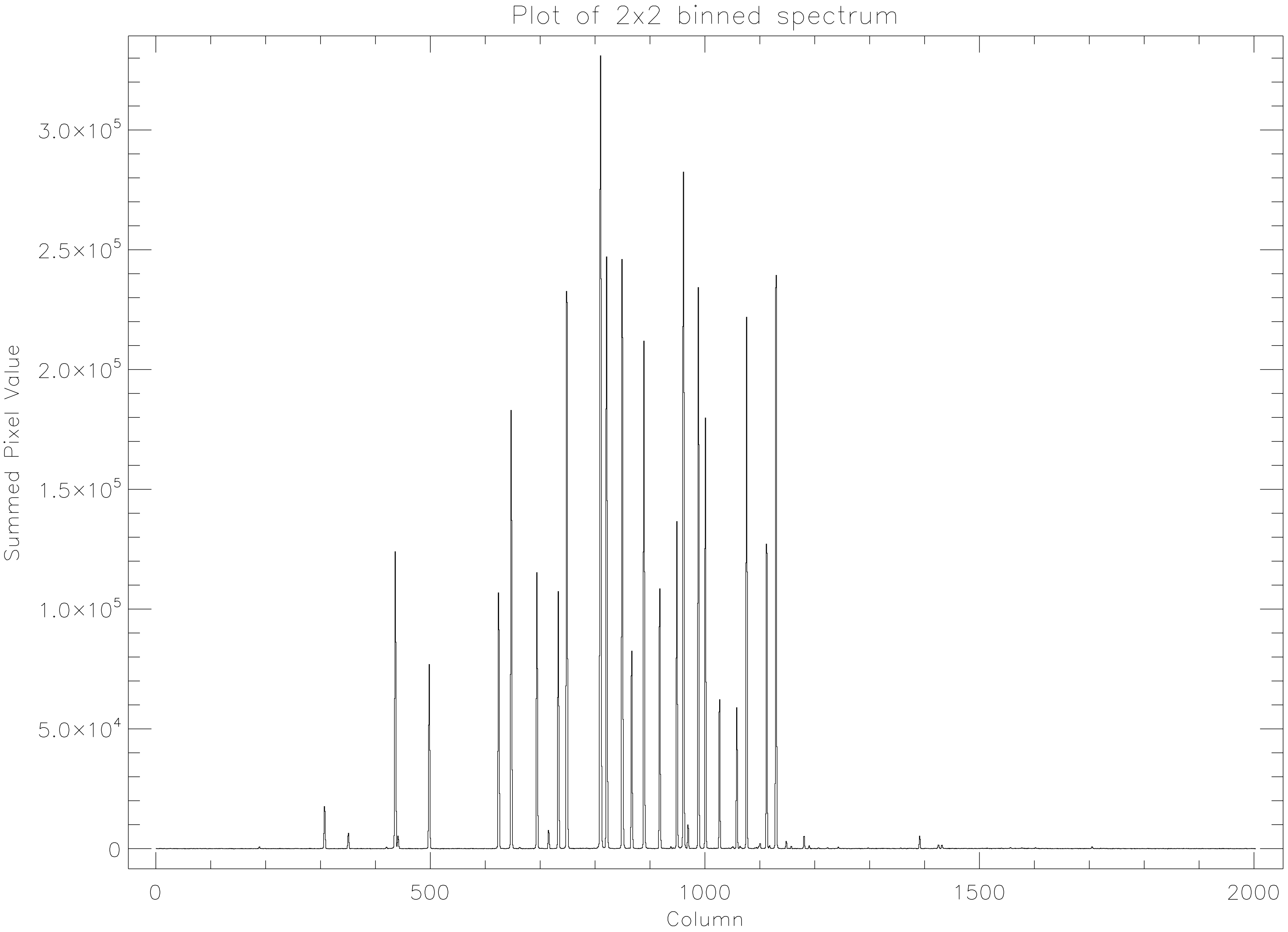
XMax: 2003.00

YMin: -90.4138

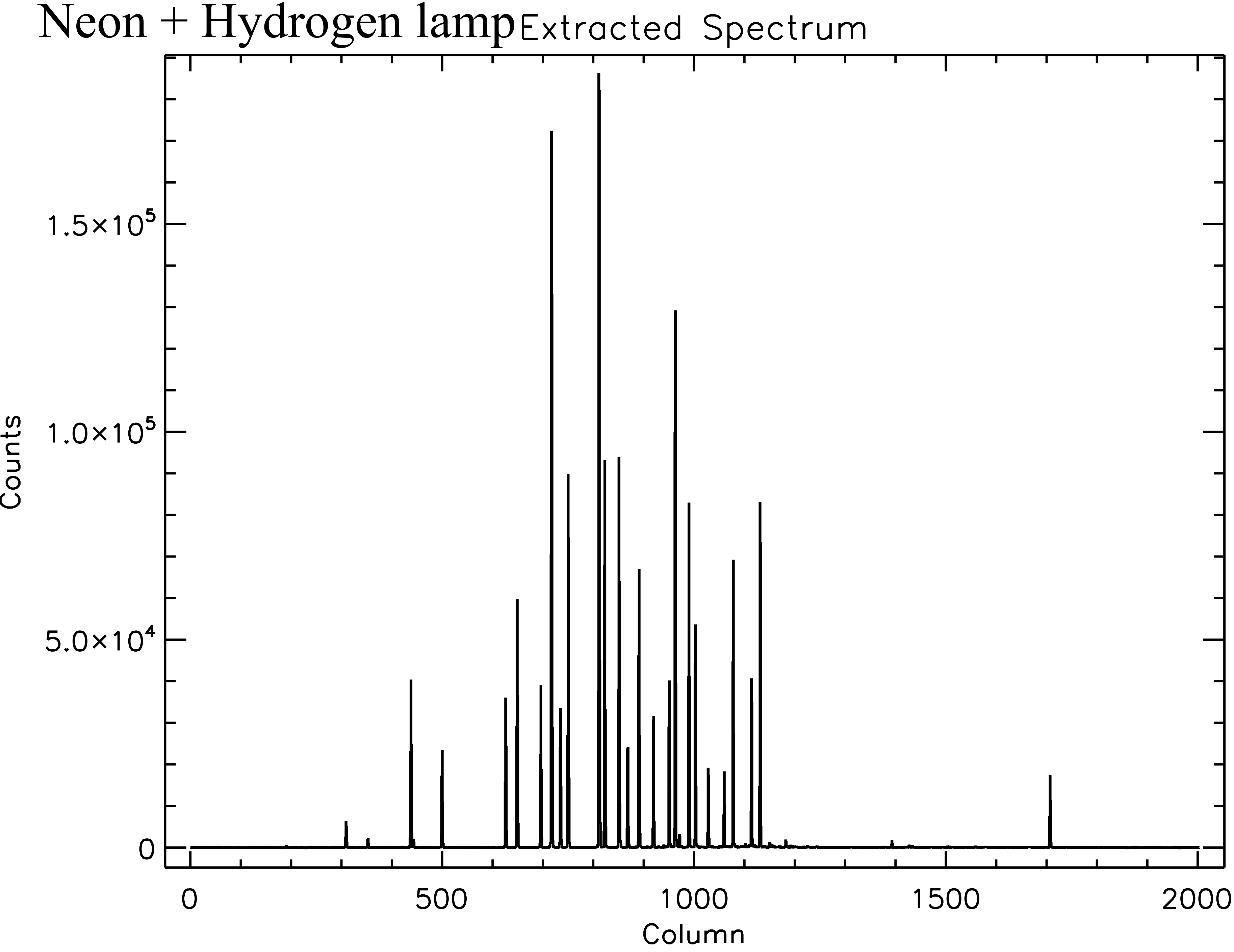
YMax: 90334.5

Charsize: 1.00000

Neon lamp spectrum



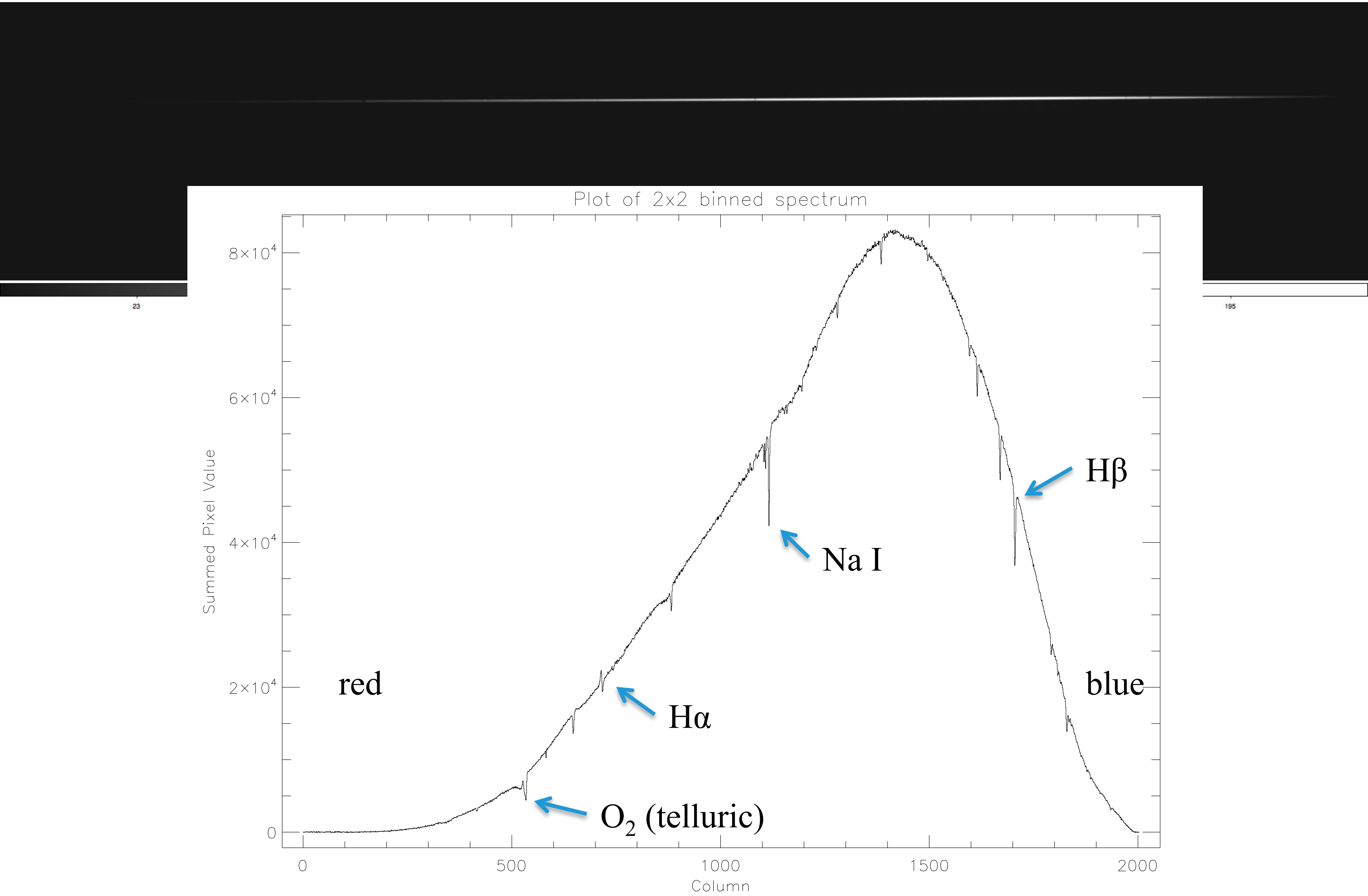
Neon + Hydrogen lamp



Processing Spectra

- Subtract dark (if not auto-subtracted)
- Extract 1-D spectrum from 2-D image
- Determine wavelength as a function of column #
  - Fit: λ = polynomial(x) using (x,λ) pairs determined by emission lines in the spectrum of a neon lamp.
  - The IDL program *neoncomp* identifies lines in the “comparison spectrum” and, given a guess at an initial $\lambda = A + B\,x$, fits polynomials of selected order.
  - A third-order (cubic) or 4th-order (quartic) give reasonable fits.

Spectrum of the Epsilon Orionis (Alnilam).



Hβ

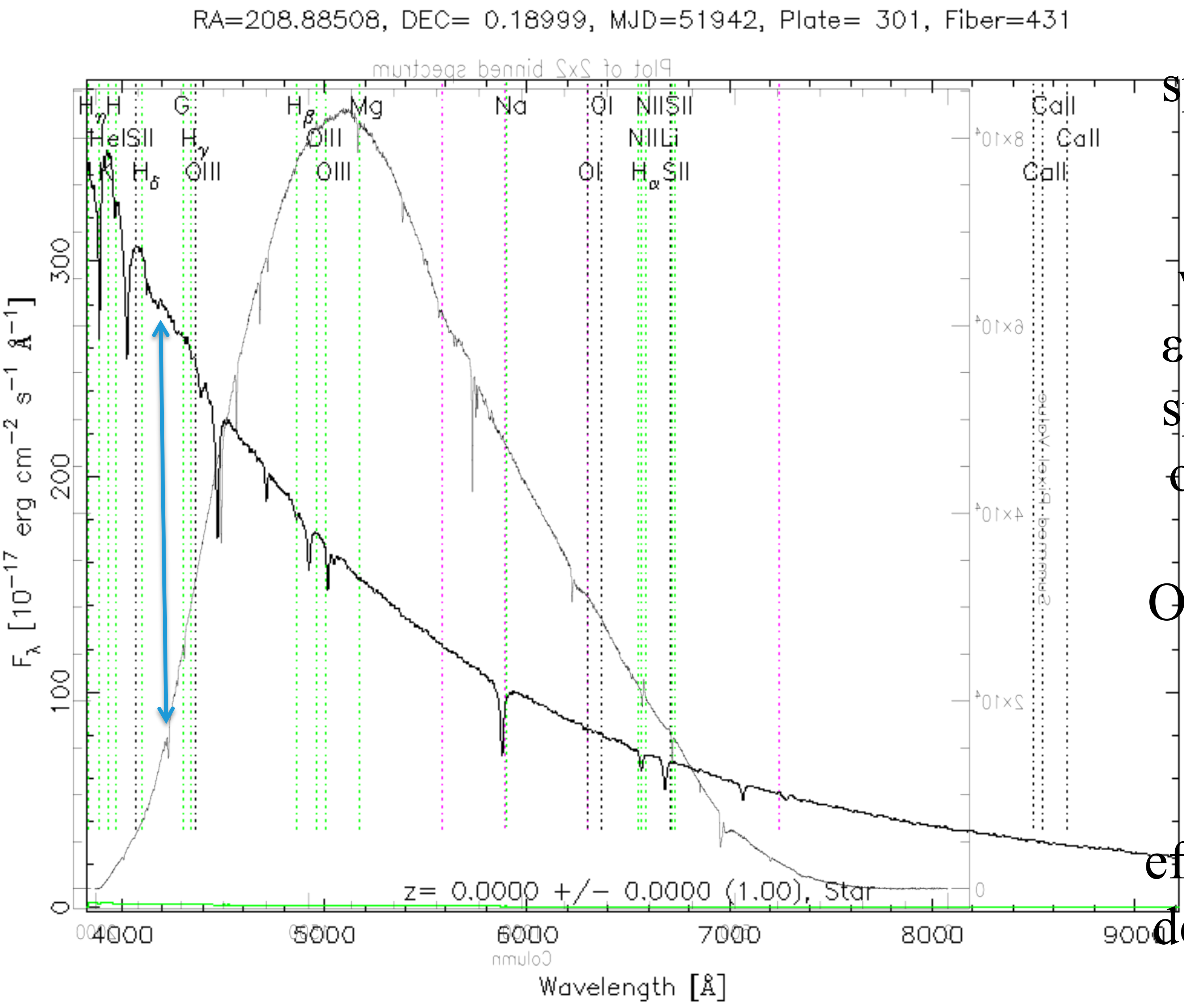
Na I

red

blue

Hα

O_2 (telluric)

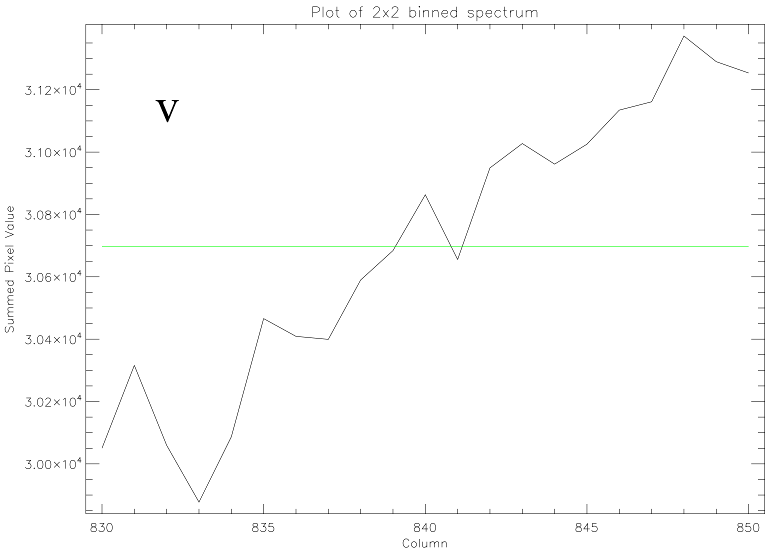


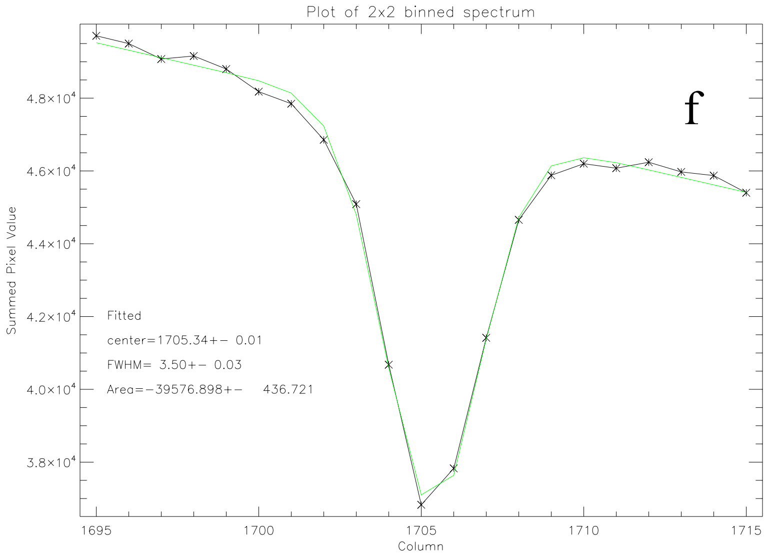
B0 star spectrum from SDSS with our ε Orionis spectrum overlaid.

Ours falls in the blue because efficiency decreases there.

Measuring Signal in a Spectrum

- The v key in *ruphst* extracts a spectrum and calculates the average value in the ±10 pixel region around the cursor location.
- The f key extracts a spectrum and fits an absorption/emission line + a sloping background (“continuum”) in the ±10 pixel region.





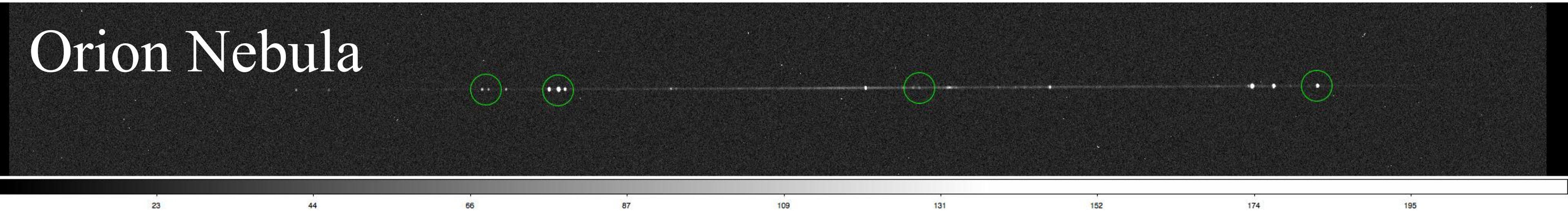
Measuring Signal in a Spectrum

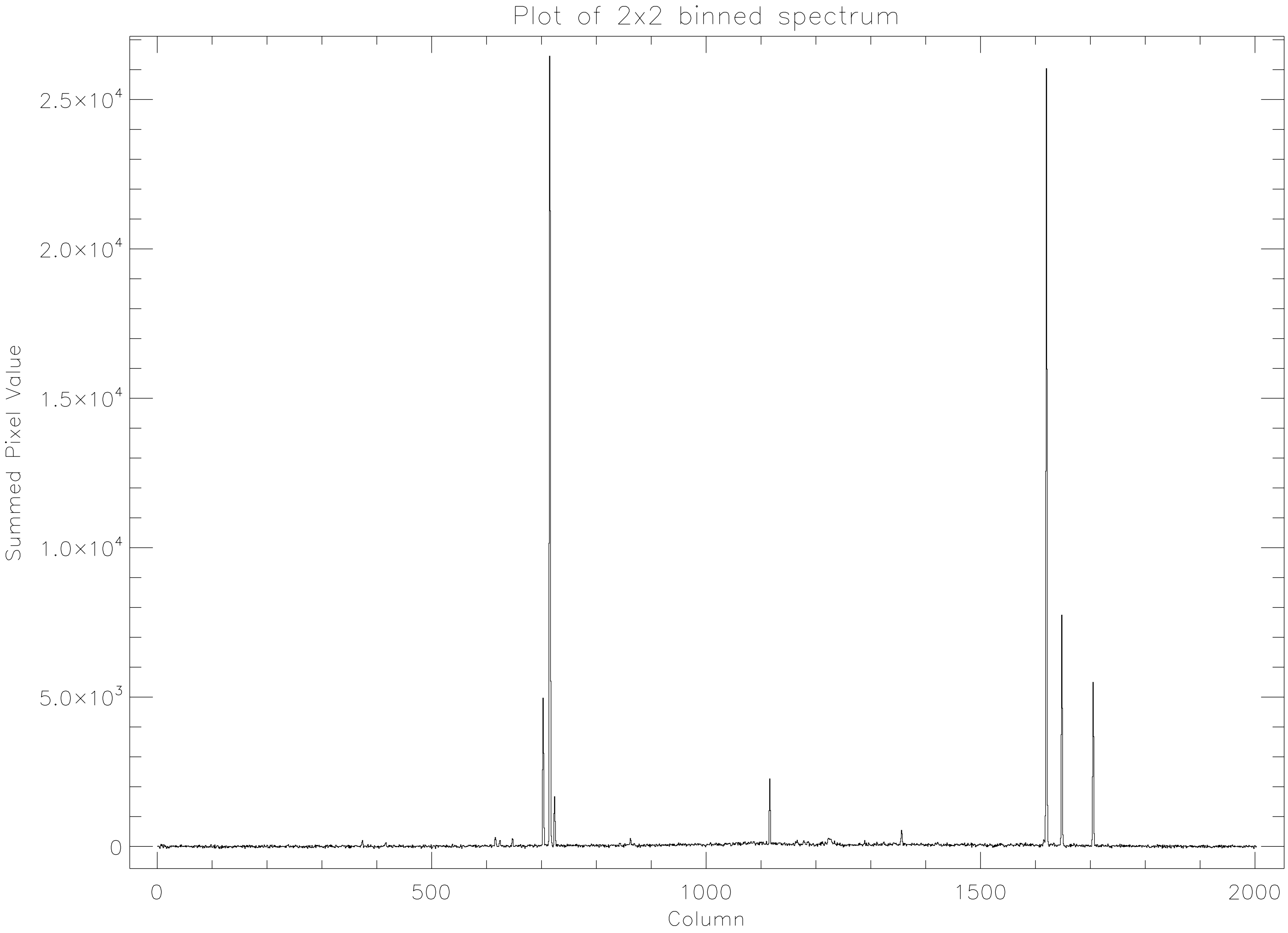
- Can calculate a relative efficiency: $f_{\lambda(x)}/s_x$
  - $f_{\lambda(x)}$ is the known flux at the wavelength $\lambda(x)$
  - s_x is the measured signal in the spectrum at x
- Multiply measured signals (total counts in the line, l_x) by efficiency to get the true (relative) flux, $j_{\lambda(x)}$.

$$j_{\lambda(x)} = l_x(f_{\lambda(x)} / s_x)$$

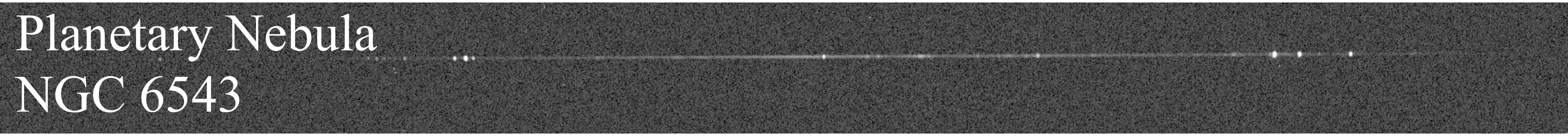
  - A subtle point is that this also corrects our measurements from photons/s to energy/s.

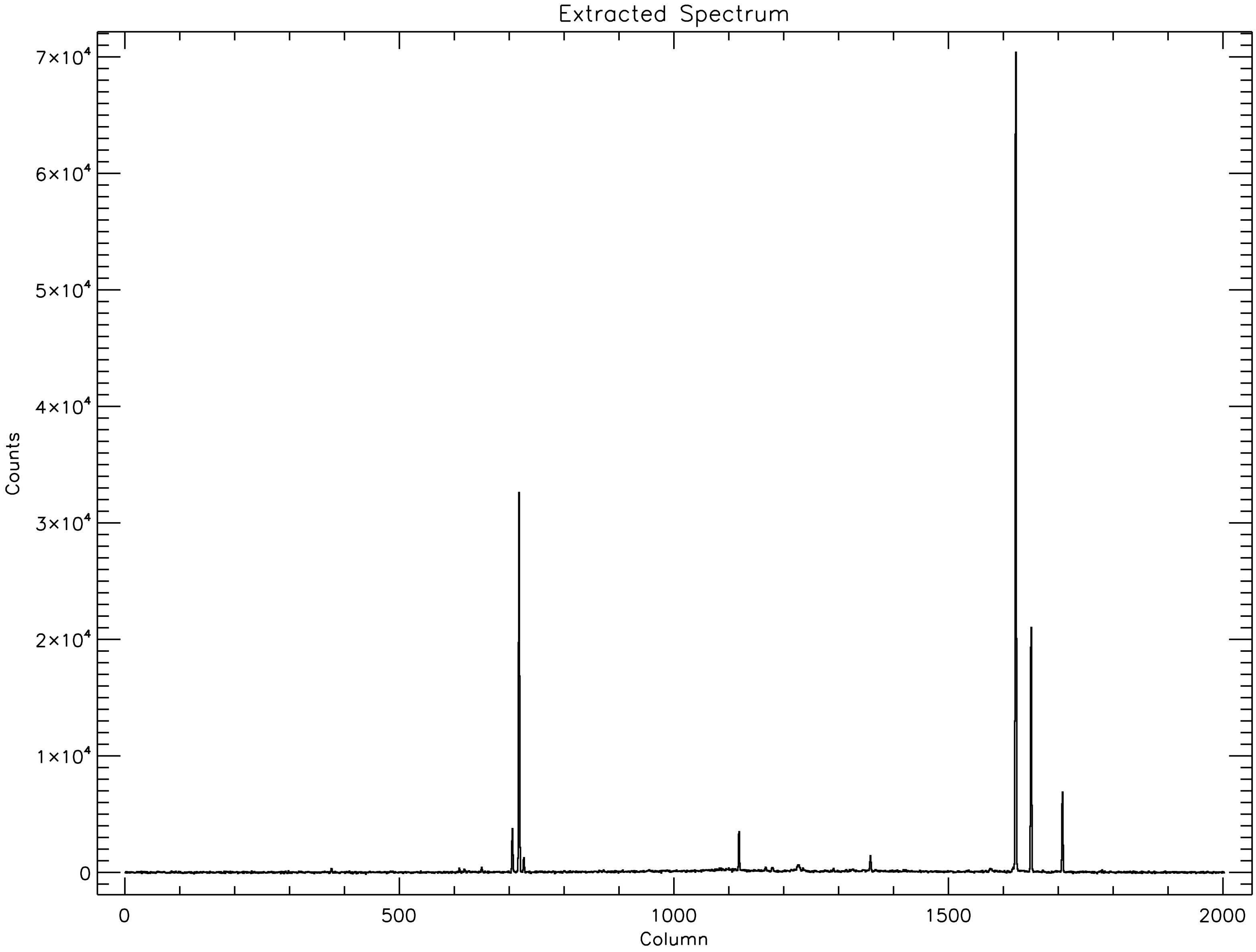
Orion Nebula





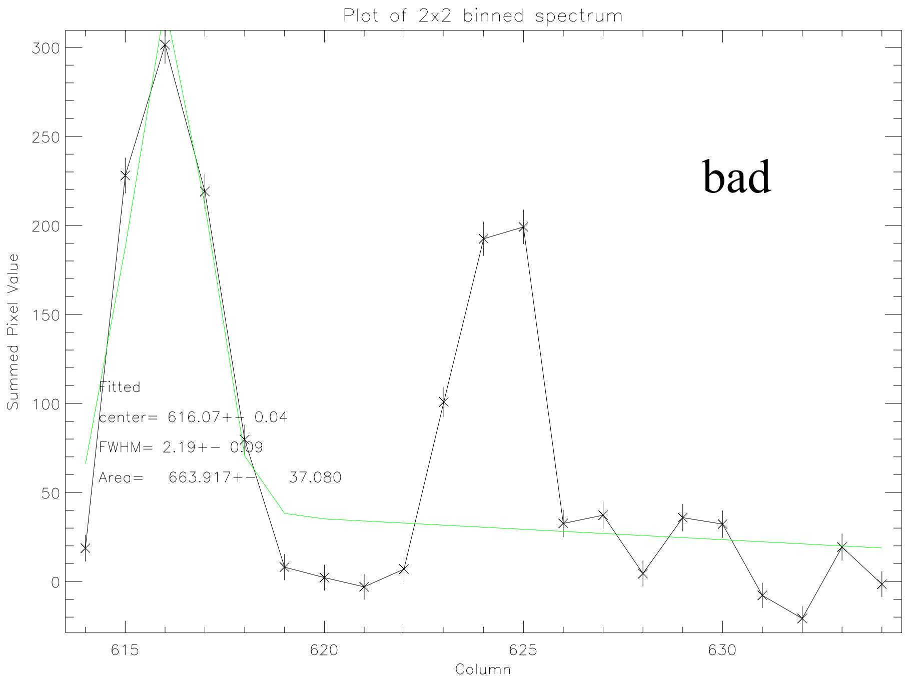
Planetary Nebula NGC 6543

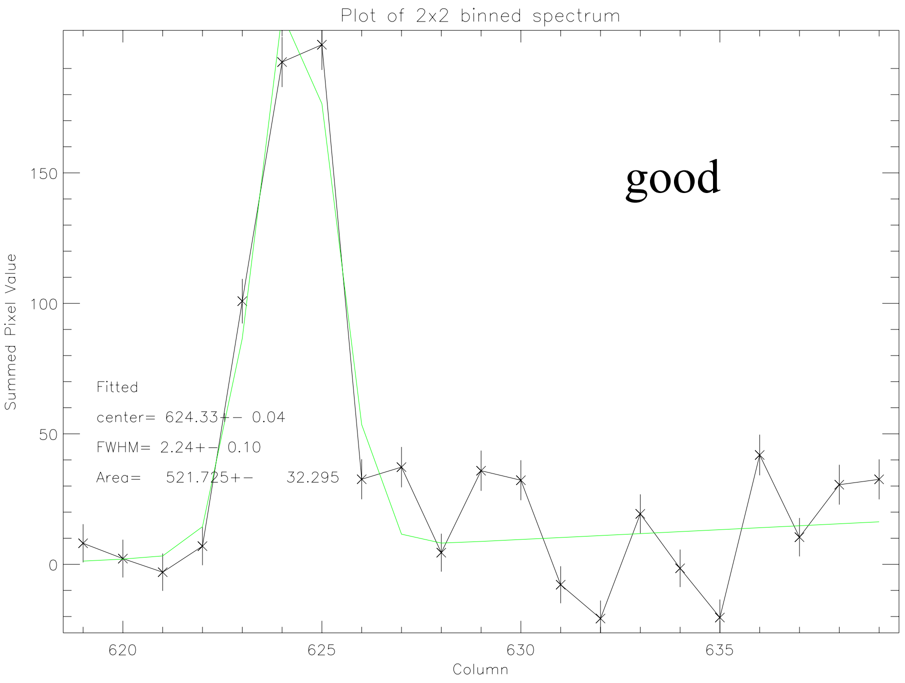




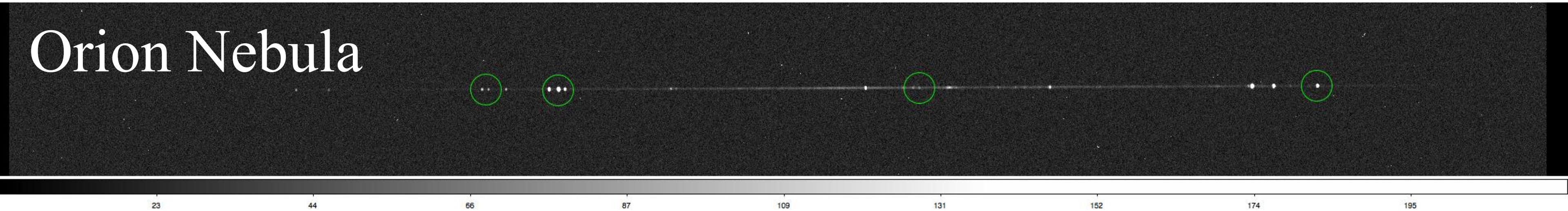
Measuring Emission Line Signal

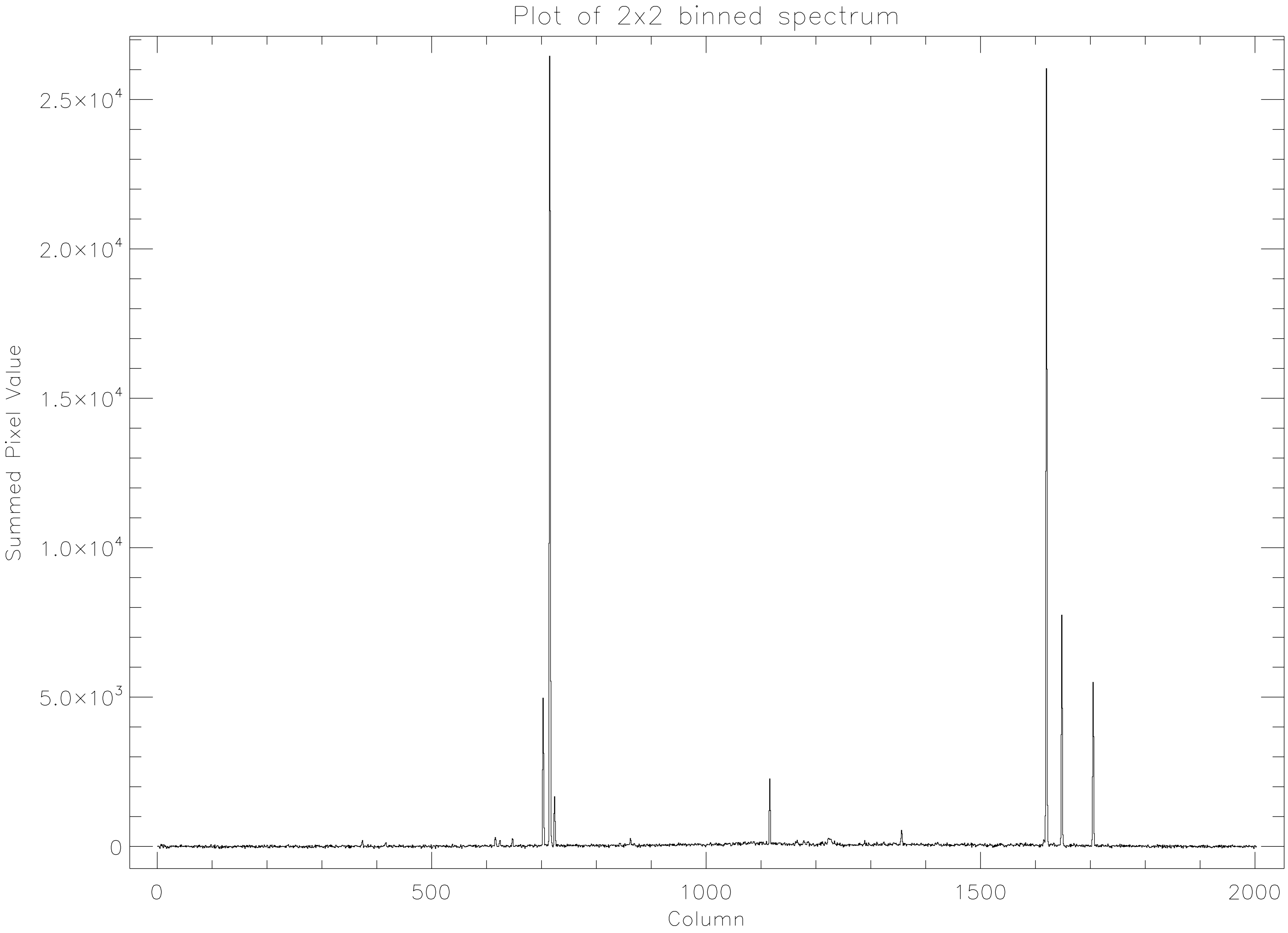
- Use the f key in *ruphast*.
  - Will need to offset the cursor from the line center in order to fit the weaker of two close emission lines.





Orion Nebula





Planetary Nebula NGC 6543