Physics 344 Lab 7
Nebular Spectroscopy Solutions

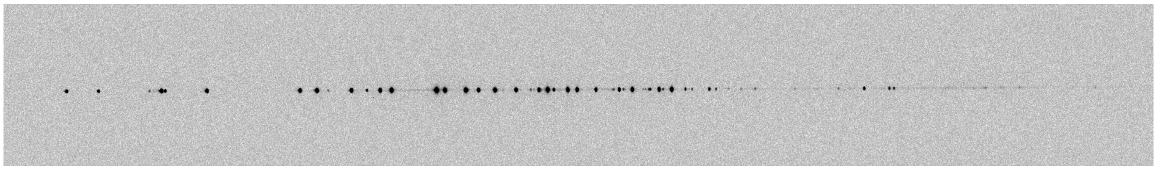
Purpose

This lab introduced the use of the fiber-fed spectrograph. Observations of a neon emission-line lamp calibrated wavelength versus pixel number. Observations of the star ε Orionis calibrated the sensitivity of the telescope + spectrograph + CCD camera as a function of wavelength. Finally, a spectrum of the Orion nebula allowed us to determine the physical conditions in the nebula.

Observations

I obtained data on the night of November 25/26, as did two groups on the evening of November 28th. Getting a star to the correct location on the CCD to have its light enter the fiber leading to the spectrograph is tricky. A major complication is the drift in the tracking of the telescope when not guiding. The best procedure was to take and save an image and then turn guiding on using a star in the image. With guiding holding the telescope fixed, the necessary offsets could be calculated at leisure. Then the guiding was turned off, the offsets applied, another image taken and saved, and then guiding turned back on. Small offsets of the telescope pointing are not that accurate, so it was necessary to iterate the above procedure until the target was at the required position.

Comparison Spectrum



A 30-second exposure neon comparison spectrum is shown in the figure above. It is dominated by bright lines in the red (center and left side), but has a few weak lines in the blue (right side) that allow a full calibration to be obtained. For an initial determination of the wavelength scale, measuring the positions of the Ne 6506.528 Å and Ne 6029.997 Å lines gave x=748.51 and x=1026.60, respectively. Fitting the linear relation $\lambda = A + Bx$ to these two lines gives:

$$A = 7789.48 \text{ Å}$$
$$B = -1.7136 \text{ Å/pixel}$$

Then running the routine *neoncomp* with these initial values finds 27 or 28 lines in the spectrum. Fits of a first- and second-order polynomial showed large systematic trends in the residuals. A third-order polynomial,

$$\lambda = A + Bx + Cx^2 + Dx^3,$$

gives a good fit to the positions of the lines with:

$A = 7739.46$ Å $\quad B = -1.57354$ Å/pixel

$C = -1.227 \times 10^{-4}$ Å/pixel^2 $\quad D = 3.260 \times 10^{-8}$ Å/pixel^3.

The RMS residual of the fitted wavelengths (compared to the actual wavelengths) is 0.14 Å and the reduced χ^2, a goodness-of-fit criterion, is 3.53. This is somewhat larger than the optimum χ^2 of 1.0. Fitting a fourth order polynomial,

$$\lambda = A + Bx + Cx^2 + Dx^3 + Ex^4,$$

reduced trends in the residuals at the ends of the spectrum. The best fit has:

$A = 7740.58$ Å $\quad B = -1.58033$ Å/pixel

$C = -1.093 \times 10^{-4}$ Å/pixel^2 $\quad D = 2.212 \times 10^{-8}$ Å/pixel^3

$E = 2.825 \times 10^{-12}$ Å/pixel^4.

The RMS residual of the fitted wavelengths is 0.12 Å and the reduced χ^2 is 2.49. The plot of the residuals suggested that one line might have been poorly measured. The FWHM of the lines is 3.02 Å. Thus, with our 2×2 binning on the spectral data, we have about 2 pixels across the line profile, critically sampling the spectra. If we were trying to get the highest precision wavelength measurements (to determine accurate radial velocities, for example), we could do a little better with unbinned (1x1) data. Higher-order polynomials give only a slight improvement in the fits.

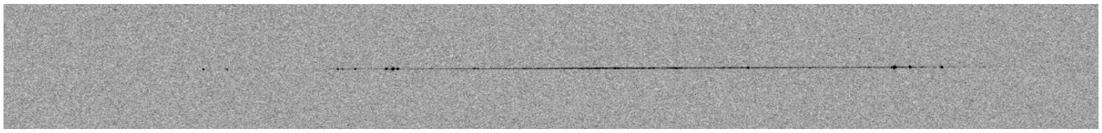
The routine polywave calculates the x positions in the spectra of the lines that we will be using in the lab:

wavelength	x
4861 Hβ	1705.3
5755 [NII]	1186.2
6548 [NII]	724.3
6563 Hα	715.5
6583 [NII]	703.8
6717 [SII]	625.0
6731 [SII]	616.2

Flux Standard

The spectrum of the star ε Orionis, a spectral type B0 supergiant, is shown above. In this very hot star there are few spectral features, making it a useful source to calibrate the flux response of the telescope+fiber+spectrograph system. Of all the wavelengths that we are measuring for this lab, the star has measurable spectral features only at Hα (a combined emission and absorption profile) and Hβ (an absorption line). The signal levels measured at each spectral position are tabulated in the last column of the table below.

M42 Spectrum



The spectrum of a bright filament in M42, the Orion Nebula, is shown above. It consists mostly of emission features, with little continuum light. The measured strengths of the features and their calculated central wavelengths are given in the table below. The brightest features are the hydrogen lines (and the 5007 [OIII] line that we did not analyze for this lab). The biggest problem that people encountered in this step was the fitting program being "captured" by a nearby stronger line. The [SII] line at 6716 Å and the [NII] line at 6548 Å were the most problematic.

Line	X	λ fit (Å)	Line Strength l	Std signal s
4861 Hβ	1705.150	4860.85	12075 ± 85	47399
5755 [NII]	1185.41	5754.87	336 ± 42	61040
6548 [NII]	723.961	6548.34	3771 ± 52	21324
6563 Hα	715.369	6562.90	62496 ± 165	20800
6583 [NII]	703.148	6583.67	11118 ± 77	18500
6717 [SII]	624.331	6717.15	522 ± 32	14680
6731 [SII]	616.083	6731.18	829 ± 36	13926

Data Analysis

Using the data from the table above, we calculate the line strength ratio for the sulfur lines:

$$j_{6717} / j_{6731} = 0.602 \pm 0.045.$$

Interpolating on the graph (figure 5.3), being sure to use the dashed line for the sulfur ratio, this gives:

$$N_e \, (10^4 \mathrm{K} / T)^{1/2} = 3.3 \times 10^3 \ \mathrm{cm}^{-3}.$$

We then calculate the line strength ratios for the nitrogen lines:

$$j_{6548} / j_{5755} = 20.5 \pm 2.6$$
$$j_{6583} / j_{5755} = 68.5 \pm 8.6$$
$$\Rightarrow (j_{6548} + j_{6583}) / j_{5755} = 89.1 \pm 8.4$$

Using the given equation and the density parameter derived above from the sulfur lines allows us to calculate the temperature in the nebula:

$$(j_{6583} + j_{6548}) / j_{5755} = (7.53 \exp(2.54\text{x}10^4\text{K} / T) / (1.0 + 2.7\text{x}10^{-5} N_e (10^4\text{K} / T)^{1/2})$$
$$\Rightarrow 89.1 = (7.53 \exp(2.54\text{x}10^4\text{K} / T) / (1.0 + 2.7\text{x}10^{-5} \text{ x } 3.3 \times 10^3)$$
$$\Rightarrow \exp(2.54\text{x}10^4\text{K} / T) = 12.89$$
$$\Rightarrow 2.54\text{x}10^4\text{K} / T = 2.556$$
$$\Rightarrow T = (9.94 \pm 0.36) \times 10^3 \text{ K}.$$

Using this value with the density parameter then gives the electron density:

$$N_e (10^4\text{K} / 9.94 \times 10^3 \text{ K})^{1/2} = 3.3 \times 10^3 \text{ cm}^{-3}$$
$$N_e = 3.3 \times 10^3 \text{ cm}^{-3}.$$

I estimated an uncertainty in the electron density of +1500 cm^{-3} and −700 cm^{-3}.

Finally, we calculate the observed Balmer line ratio from the hydrogen lines:

$$J_{H\alpha} / j_{H\beta} = 4.270 \pm 0.032.$$

For a $N_e=10^4 \text{ cm}^{-3}$, $T=10^4$ K gas we expect $j_{0H\alpha} / j_{0H\beta} = 2.85$ (for Case B recombination). Thus, there is a significant amount of dust that is reddening the line ratios. We calculate an extinction c of:

$$J_{H\alpha}/j_{H\beta} = (j_{0H\alpha}/j_{0H\beta}) 10^{0.35 c}$$
$$10^{0.35 c} = 1.498$$
$$0.35 c = 0.176$$
$$c = 0.50$$

Given the dusty appearance of the Orion nebula, it is not surprising that there is a measurable extinction within the nebula. To be fully consistent in our analysis, we should correct the nitrogen line ratios above for this extinction, and then recalculate the temperature and density. The sulfur lines are so close in wavelength that the effect of differential extinction on their line ratio is negligible.