

Due: Thursday, December 8

Purpose: Spectroscopy is the most powerful tool of modern astronomy. By breaking the light from celestial objects into its component colors and measuring the intensity of each color, we can determine many of the important physical characteristics of these objects. The Orion Nebula, also known as M42, is one of the closest regions to the Sun where large numbers of massive stars are currently being formed. It is being intensively studied by astronomers to investigate the details of the star formation process. M42 is an emission nebula (also called an HII region): a cloud of hydrogen ionized by the ultraviolet light from hot (massive) young stars embedded in the nebula. For the Orion Nebula, most of the ionizing light comes from a group of O and B stars called the Trapezium. The diffuse emission of the nebula comes from recombination lines of hydrogen, and “forbidden” lines of nitrogen, oxygen, and sulfur. In this lab we will use a fiber-fed spectrograph to obtain spectra of the nebula and from them determine the temperature and density of the interstellar gas.

Observations: Turn on the telescope controller and the direct CCD in the usual way, and also the spectrograph CCD, with the switch under the desk beside the spectrograph. Start *The Sky* and two instances of the CCD control software using the icons labeled *Image* and *Spectrograph*. Note that the control programs for the two CCD systems are virtually identical. Be careful to distinguish between them when running the detectors! Cool both CCDs to as low a temperature as possible, and let the systems stabilize. Setup *AutoSave* on both programs to use an appropriate directory in Lab7 on the G: disk. Start *IDL* and *ruatv*; there are two single-key routines in *ruatv* for examining spectra: “e” extracts and plots the spectrum, with background subtraction, and “f” fits the spectral line at the cursor position.

1. Comparison Spectra

- a. Using the knob on the front the spectrograph, set the wavelength to 615 nm. We will use this setting for all the spectra in this lab, so do not change this setting for the rest of the lab.
- b. The fiber that feeds light to the spectrograph is illuminated by a small mirror that diverts part of the beam of the telescope. This mirror is moved by the actuator on the side of the instrument box near the direct CCD. Put the spectrograph mirror in the “Fiber” position.
- c. Set up the neon lamp on the ladder and move the telescope to point at the lamp. Turn on the lamp and make sure that it is shining on the telescope primary mirror.
- d. On the *Take Image* tab of the spectrograph CCD control program, select full frame mode with 2x2 binning and *Light* frame with *AutoDark*

processing. Use any of the filter positions – they are all open with no filters installed.

- e. Make sure that the AutoSave is turned on for the spectrograph CCD, and take a 30 second exposure. The brightest red lines (left center of the image) should be just about saturating, while the few faint lines in the blue (right side of the image) should be measurable.
- f. Turn off the neon lamp and store it on the observing desk. Put the telescope in the home position.

2. Darks

- a. On the *Take Image* tab of the spectrograph CCD control program, maintain full frame mode with 2x2 binning. Select *Dark* frame with processing *None*.
- b. Turn off the dome lights and take two 300-second dark exposures.

3. Focus

- a. Put the spectrograph mirror back to the *Direct* position. Switch to the image CCD control program and setup for full frame with 2x2 binning, and the V filter.
- b. Point the telescope to a bright star in the eastern part of the sky (Aldebaran is a good choice). Center the star in the finder telescope and synch the telescope.
- c. Point the telescope to a star of about 8th magnitude near the constellation Orion. Focus the telescope onto the direct CCD in the normal way.

4. Standard Star

- a. Point the telescope to Epsilon Orionis (the middle star in Orion's Belt, aka Alnilam, HIP 26311, or HD 37128).
- b. Set up the direct CCD for full frame, 2x2 binning, *Light* frame, and *AutoDark* processing. Select a short exposure time (about 0.1 second) so that E Ori is not saturated. Use *ruatv* for inspecting the images.
- c. In the *Autoguide* tab of the direct image CCD control program, select the Imager radio button. Run the *Calibrate* routine, using E Ori.
- d. Use the *Motion Controls* on the *Telescope* tab of *The Sky* to move E Ori to coordinates x=1140, y=690 of the direct CCD. At this position, when the spectrograph mirror is inserted the star's light will illuminate the spectrograph fiber. For objects in the eastern part of the sky, moving the telescope East will move the image up (larger y) in the CCD, as seen in *ruatv*; moving North will move the image to the right (larger x). The image scale in 2x2 bin mode is about 1" per pixel.
- e. When Epsilon Orionis is at the correct position, synch the telescope again (in *The Sky*).
- f. Make sure that you have turned off AutoSave for the direct images. In the *Autoguide* tab of the direct image CCD control program set the exposure time to 2 seconds. Take an image and verify that Epsilon Orionis is still at position 1140, 690. There should be a good guide star near coordinates 450, 245. Click on this star, and then start

autoguiding. Wait for several guide cycles to allow the guiding to stabilize.

- g. Carefully slide the spectrograph mirror to the *Fiber* position. This should not affect the autoguider.
- h. Switch to the Spectrograph CCD control program. On the Take Image tab, setup for a full frame 2x2 binned *Light* frame with *AutoDark* reduction. Take a 120-second exposure.
- i. Use the *ruatv* program to inspect the spectrum – put the cursor near the spectrum and press the “e” key to extract and plot it. There should be about 3000 ADU at the peak of the spectrum. If the spectrum is weak or absent, you probably don’t have the star centered on the fiber – realign the star and try again (steps f-h above).
- j. When you have a good spectrum, take 2 more, each of 120 seconds.

5. Nebula

- a. Turn off the autoguider, and then point the telescope to the Orion Nebula (M42). Move the spectrograph mirror to the *Direct* position. Using 2-second exposures on the direct CCD, position a bright part of the nebula to coordinates 1140, 690, but do not put any of the bright stars there.
- b. There should be a good guide star near position 660, 390. Set up the autoguider and start autoguiding on this star.
- c. Carefully slide the spectrograph mirror to the *Fiber* position. This should not affect the autoguider.
- d. Switch to the Spectrograph CCD control program. On the Take Image tab, setup for a full frame 2x2 binned *Light* frame with reduction *None*. Take a 300-second exposure.
- e. Check the spectrum with *ruatv*. There should be several bright emission lines. If there is no spectrum, make sure that you put the spectrograph mirror in the *Fiber* position (step c above), and then review steps a-d above.
- f. When all is well, take two more 300-second exposures.

6. Darks

- a. Take two more 300-second dark exposures with the Spectrograph CCD (see step 2 above).

Data Reduction:

1. Copy your data to a working directory in your home area, and only work on the copies, not the original images.
2. Run the IDL routine *ruatv* and display your comparison spectrum. Locate the bright neon lines at wavelength 6506.528 Å (near x = 747) and at 6029.997 Å (near x = 1026). Use the “f” key to fit these lines with a Gaussian function, and record the fitted center position. Fit a linear function to these two spectral lines and record the coefficients of the fit for use in the next step:

$$\lambda = A + B x$$

3. Use the IDL program *neoncomp* to analyze your comparison spectrum. After selecting the comparison spectrum image, answer the next two questions with your approximate wavelength zeropoint and dispersion (A and B) from step 2 above. The program first displays the extracted spectrum to make sure that there are no terrible mistakes – press the “enter” key to continue. The program then displays each of 28 neon spectral lines from your spectrum and a fitted Gaussian function – press “y” to accept the line or “n” to reject it (you will normally accept all 28 lines). After you have examined each line, the program does a linear fit to wavelength as a function of position for the lines that you accepted, and displays the residuals about that fit. Information about the fit is displayed in the IDL message window. Try other fit orders to see the effects: 2 (quadratic) and 3 (cubic) are interesting. When you are satisfied with the fit, enter a 0 to end the program. Record the fit order, the fit coefficients, the RMS fit error, and the line FWHM (in Å) for your report. The program writes a text file, *wavecal.dat*, containing the fit information, for later use.
4. After running *neoncomp*, use the IDL program *polywave* to use the calibration fit to determine the positions of the spectral features to be used in this lab. *Polywave* will read the *wavecal.dat* file and then prompt you for a wavelength. Enter each of the wavelengths in the table of step 8, and record the x value that *polywave* calculates. Save these positions for later use.
5. Use the IDL routine *mkdark* to combine your 4 dark images into a master dark image.
6. Process each of your nebula spectra with the program *spproc*. This routine is similar to *diproc* used in Lab 6, but it only subtracts the dark image.
7. Combine the three processed spectra of the nebula using the routine *shiftcombine*. There should be no shifts between the spectrum images, so answer each question about the x and y shifts with “0 0” (don’t type the quotation marks).
8. Display the combined nebula spectrum with *ruatv*. Measure the line strength (area under the fitted curve) for the spectral lines in the following table. Use the positions you calculated in step 4 above as an aid to identifying which line

is which, and then use the *ruatv* “f” key to fit the line. In your report, include the fitted position of the line and the line strength (area under the fitted curve).

Wavelength (Å)	Source
6731	[SII]
6716	[SII]
6583	[NII]
6563	H α
6548	[NII]
5755	[NII]
4861	H β

- Combine the three standard star images (that were autodark subtracted at the telescope) with *shiftcombine*. Again, all the shifts will be “0 0”. Display the combined spectrum using *ruatv*, and measure the flux at the positions in the spectrum at each of the wavelengths in the table above. For the H β line, position the cursor to the correct x position (around 1704) and use the “f” key to fit the absorption line; record the value of the “continuum at the line center” that is printed in the IDL output window. For all the other lines, position to cursor to the proper x position and use the “v” key; record the “mean flux” value that is printed out. These are the “s” values used in step 10.
- Use your measurements and the standard fluxes for Epsilon Orionis from the table below to calculate line ratios using the following relation:

$$\frac{j_a}{j_b} = \frac{l_a}{l_b} \frac{\lambda_b}{\lambda_a} \frac{f_a}{f_b} \frac{s_b}{s_a}$$

where j_a is the true strength (energy received) of line a, l_a is the measured line strength, λ_a is the wavelength, f_a is the standard star flux, and s_a is the measured standard star continuum level. The Epsilon Orionis fluxes, f , are:

wavelength	flux
4861 H β	12.746
5755 [NII]	8.618
6548 [NII]	6.267
6563 H α	6.235
6583 [NII]	6.188
6716 [SII]	5.901
6731 [SII]	5.868

11. Calculate the [SII] line ratio j_{6716} / j_{6731} and then use the graph below to determine the value of the quantity $N_e (10^4 K / T)^{1/2}$.

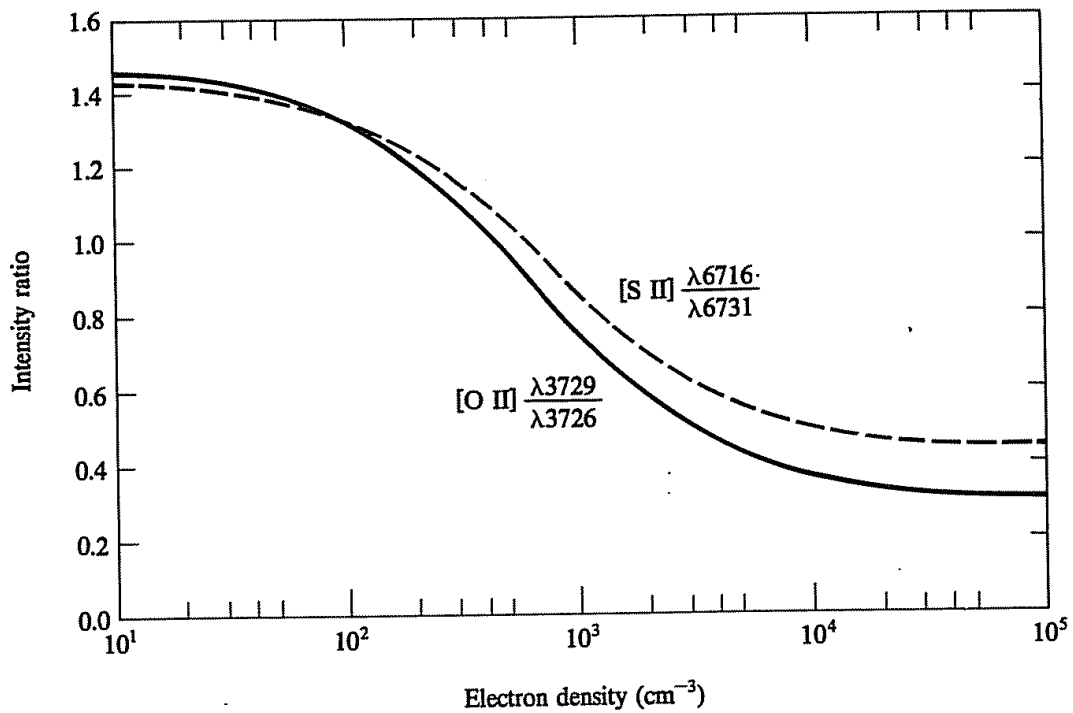


FIGURE 5.3
 Calculated variation of [O II] (*solid line*) and [S II] (*dashed line*) intensity ratios as function of N_e at $T = 10,000^\circ \text{K}$. At other temperatures the plotted curves are very nearly correct if the horizontal scale is taken to be $N_e(10^4/T)^{1/2}$.

12. Calculate the [NII] ratios j_{6548}/j_{5755} and j_{6583}/j_{5755} and then sum these values to produce $(j_{6548} + j_{6583})/j_{5755}$. Then use the following equation and your value of Ne $(10^4 K / T)^{1/2}$ from step 11 to calculate the temperature, T.

$$\frac{j_{6548} + j_{6583}}{j_{5755}} = \frac{7.53 \exp(2.54 \times 10^4 K/T)}{1.0 + 2.7 \times 10^{-5} N_e (10^4 K/T)^{1/2}}$$

13. Use the temperature that you calculated in step 12 and the result of step 11 to calculate the electron density N_e
14. Now determine the Balmer line ratio $j_{H\alpha}/j_{H\beta}$ from your spectra. Then use the table below to determine the expected Balmer line ratio, $j_{0H\alpha}/j_{0H\beta}$. The difference between the observed and expected line ratios is due to interstellar extinction. Calculate the amount of extinction, c , from the relation:

$$\frac{j_{H\alpha}}{j_{H\beta}} = \frac{j_{0H\alpha}}{j_{0H\beta}} 10^{0.35c}$$

TABLE 4.4
H I recombination lines (Case B)

	T							
	5000° K		10,000° K			20,000° K		
	10 ²	10 ⁴	10 ²	10 ⁴	10 ⁶	10 ²	10 ⁴	
N_e (cm ⁻³)	10 ²	10 ⁴	10 ²	10 ⁴	10 ⁶	10 ²	10 ⁴	
$4\pi j_{H\beta}/N_e H_e$ (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 H β								
$j_{H\alpha}/j_{H\beta}$	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	