Physics 344   Lab 7
Nebular Spectroscopy

Observing: We will use previously-taken data.
Due: Wednesday, December 12

I. 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 early groups will obtain a spectrum of the planetary nebula NGC 7027 and the late groups a spectrum of the Orion Nebula, also known as M42. Both are examples of an emission nebula (also called an HII region): a cloud of hydrogen ionized by the ultraviolet light. This light comes from a hot white dwarf in the case of planetary nebula and from hot (massive) young stars embedded in the nebula in the case of M42. The diffuse emission of an HII region 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.

M42 is one of the closest regions to the Sun where large numbers of massive stars are currently being formed and is being intensively studied by astronomers to investigate the details of the star formation process. In the Orion Nebula, most of the ionizing light comes from a group of O and B stars called the Trapezium.

The planetary nebular NGC 7027 is small and has a high surface brightness, suggesting that it has just begun its expansion and so is relatively young.

II. Observations:
I have included this description in the lab to give you an idea of how the spectroscopic data are obtained, but we will use previously-taken data to do the analysis starting in Part III. These data are available in /home/ph344/lab7.

Turn on the telescope controller and start *The Sky*. Turn on the direct CCD and start the *CCDSoft* program to control it. Then turn on the spectrograph CCD with the switch under the desk beside the spectrograph and start a second instance of the *CCDSoft*. 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 (about 40° C below ambient temperature), and let the systems stabilize. Set up *AutoSave* on both programs to use an appropriate directory in Lab6 on the G: disk. Start *IDL* and *RUPhAst*; there are two single-key routines in *RUPhAst* 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. Move the telescope so that you can hold the neon lamp in front of it. 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. Focus
    a. Put the spectrograph mirror back to the *Direct* position. Switch to the image CCD control program and set up for full frame with 2x2 binning, and the V filter.
    b. Initialize and refine the pointing of the telescope using a bright star in the western part of the sky for the early groups or the eastern part of the sky for the late groups.
    c. Point the telescope to a star of about 8th magnitude near the target nebula. Focus the telescope onto the direct CCD in the normal way.

3. Standard Star
    a. Early groups will use the star Vega as a spectrophotometric standard and late groups will use 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 Vega or ε Ori is not saturated. Use *RUPhAst* for inspecting the images.
    c. In the *Autoguide* tab of the direct image CCD control program, select the Imager radio button, then return to the *Take Image* tab.
    d. Use the *Motion Controls* on the *Telescope* tab of *The Sky* to move the standard star 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 *RUPhAst*; moving North will move the image to the right (larger x). When looking west, the directions are West and South, respectively. The image scale in 2×2 bin mode is about 1" per pixel.

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e. When the standard star 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. Select a good guide star on the left side of the image. 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 30-second exposure for Vega, a 120-second exposure for ε Ori.

i. Use the *RUPhAst* program to inspect the spectrum – put the cursor near the spectrum and press the "x" key to extract and plot it. There should be about 3000 ADU at the peak of the spectrum (or even higher for Vega). 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 30 or 120 seconds.

4. Nebula

a. Turn off the autoguider, and then point the telescope to NGC 7027 or 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. Set up the autoguider and start autoguiding on a good guide 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 30-second exposure.

e. Check the spectrum with *RUPhAst*. 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, set the reduction to *AutoDark* and take three 600-second exposures.

III. Data Reduction and Analysis:

1. Copy your data to a working directory in your home area, and only work on the copies, not the original images.

2. Combine the three auto-dark-subtracted spectra of the comparison star 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). Give the combined image some reasonable name. Similarly combine the three auto-dark subtracted spectra of the nebula

3. Start *RUPhAst* and display your neon comparison spectrum. Locate the bright neon lines at wavelength 7032.413 Å (near x = 439) and at 5852.488 Å (near x = 1132). 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:

$$\lambda = A + B\,x$$

4. Read your combined Vega or ε Ori spectrum into *RUPhAst* (without deleting your neon spectrum). Display your standard star spectrum with the x key. In the *phast spectral extraction* window, change the lower background region to be −35 to −15 and the upper background region to be 15 to 35. Remember to hit return after entering new numbers. Push the *Toggle parameter hold* button. This will fix the spectral extraction aperture. Display your neon spectrum and plot the spectrum with the x key. Use the *Write spectrum as FITS* button to write the extracted one-dimensional neon spectrum to a file (say spec-neon1d.fit).

5. Use the IDL program *neoncomp* to analyze your comparison spectrum. Select the one-dimensional neon comparison spectrum image and then answer the next two questions with your approximate wavelength zeropoint and dispersion (A and B) from step 3 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 30 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 30 lines). After you have examined each line, the program fits a linear function to wavelength *versus* position for the lines that you accepted and displays the residuals from that fitted function. Information about the fit is displayed in the IDL message window. Try fitting polynomial functions with different orders to see the effects: 2 (quadratic), 3 (cubic), 4 (quartic), and 5 (quantic) 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.

6. 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 7 and record the x value that *polywave* calculates. Save these positions for later use.

7. Display the combined nebula spectrum with *RUPhAst*. Again use the combined standard star spectrum to determine the extraction aperture, then fix the aperture and use it to display and fit lines in the combined nebula spectrum. Measure the line strength (area under the fitted curve) for the spectral lines in the following table. Use the positions you calculated in step 5 above as an aid to identifying which line is which, and then use the *RUPhAst* "*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). Be warned that the fit adopts the largest pixel value in a several-pixel window around the initial cursor position as the first guess for the position of the line. When you are

trying to fit a weak line adjacent to a strong line, this feature can cause the fit to be "captured" by a strong line. To fit the weak line you need to move your initial cursor position away from the strong line so it falls outside the window. Try steps of one pixel in the initial position until you fit the line that you want.

Wavelength (Å)	Source
6731	[SII]
6716	[SII]
6583	[NII]
6563	Hα
6548	[NII]
5755	[NII]
4861	Hβ

8. Display the combined standard star spectrum using *RUPhAst* and measure the flux at the positions in the spectrum at each of the wavelengths in the table above. For the Hβ 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 of 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 9.

9. Use your measurements and the standard fluxes for Vega or ε Orionis from the table below to calculate line ratios using the following relation:

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

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

Wavelength (Ångstroms)	Vega flux (10^{-9} erg/cm²/s/Å)	ε Ori flux (10^{-9} erg/cm²/s/Å)
4861 Hβ	4.62	5.50
5755 [NII]	3.14	3.14
6548 [NII]	1.81	2.01
6563 Hα	1.86	1.99
6583 [NII]	1.82	1.97
6716 [SII]	1.96	1.84
6731 [SII]	1.95	1.83

10. Calculate the [SII] line ratio j_{6716}/j_{6731} and then use the graph below to determine the value of the quantity N_e $(10^4 \text{ K} / T)^{1/2}$. Here N_e is the electron density in the nebula and T is the temperature of the electrons.
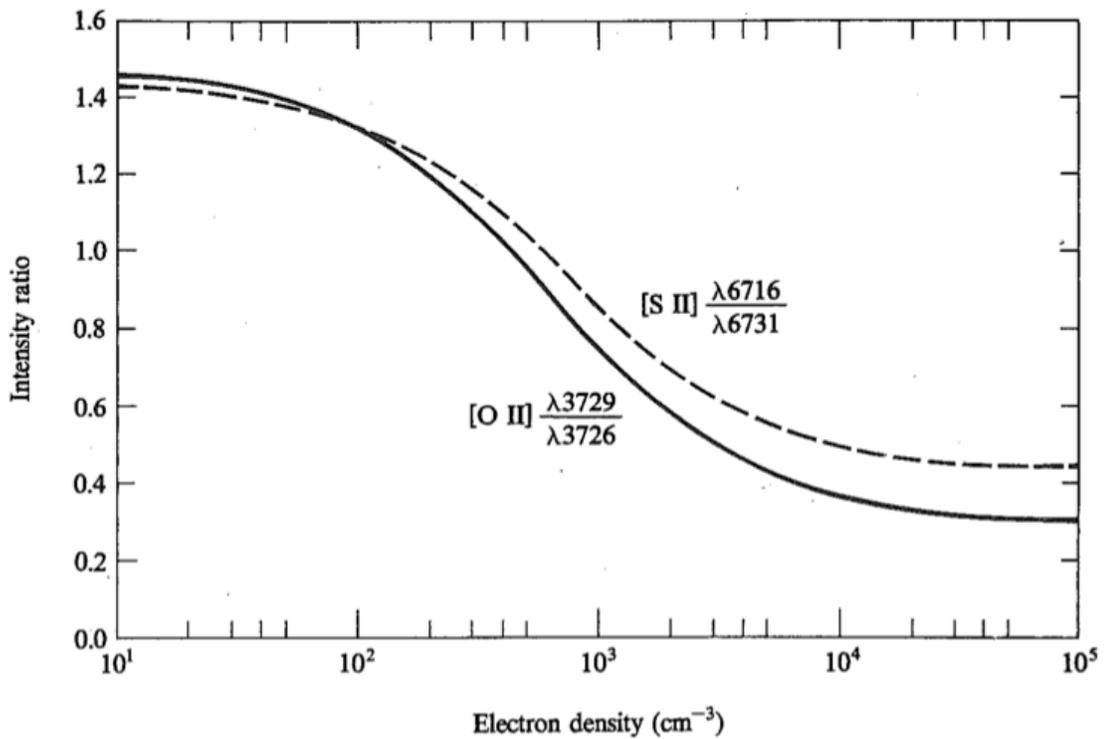

FIGURE 5.3
Calculated variation of [O II] (*solid line*) and [S II] (*dashed line*) intensity ratios as function of N_e at T = 10,000° K. At other temperatures the plotted curves are very nearly correct if the horizontal scale is taken to be $N_e(10^4/T)^{1/2}$.

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11. 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 $N_e(10^4 K/T)^{1/2}$ from step 10 to calculate the temperature, T.

$$\frac{j_{6548} + j_{6583}}{j_{5755}} = \frac{6.91\exp(2.50\times10^4 K/T)}{1.0 + (2.5\times10^{-5} cm^3)N_e(10^4 K/T)^{1/2}}$$

12. Use the temperature that you calculated in step 11 and the result of step 10 to calculate the electron density N_e.

13. 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	
N_e (cm^{-3})	10^2	10^4	10^2	10^4	10^6	10^2	10^4	
$4\pi j_{H\beta}/N_p H_e$ (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 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	