Diffuse Nebula Lab

1. Equipment

- high-resolution DADOS spectrograph
- ST402ME CCD camera (NOT the big STL1001 camera)
- Orion StarShooter AutoGuider
- same laptop as for imaging lab

2. Targets

- a high surface brightness diffuse nebula (a star-formation region or a bright planetary nebula)
- a B or A type star brighter than mag 3, within 20 degrees of the target, as spectrophotometric reference star

3. General Strategy

- Obtain a 3500-7000 Å spectrum of a diffuse nebula. Also take a spectrum of a bright reference star of type B or A, with the same settings.
- The most visible-wavelength common lines in ionized nebulae will be due to hydrogen (the Balmer series), singly-ionized helium (He II), and forbidden lines from ionized oxygen [O II], [O III], nitrogen [N II], and sulphur [S II]. Your goal is to measure the following lines:
  - Hγ, Hβ, Hα (4341, 4861, 6563 Å)
  - He I (5876 Å)
  - [N II] (5755, 6548, 6583 Å)
  - [O III] (4363, 4959, 5007 Å)
  - [O II] (3729, 3726 Å)
  - [S II] (6716, 6731 Å)
- Because the spectral range of the spectrograph is about 700 Å, you will have to do this in several takes, by adjusting the angle setting of the diffraction grating. Every time you change the wavelength setting, make sure to take a spectrum of the reference star: this is so that you can calibrate the throughout as a function of wavelength.
- For each wavelength setting, take a spectrum of the Neon and/or Mercury arc lamp for wavelength calibration.

- The most efficient procedure, one that involves the smallest number of grating angle changes, would be to scan the entire nebula in one grating setting with spectra and images, observe the standard star, change the grating setting, and repeat while trying to point roughly at the same locations. If the telescope pointing is too sporadic, first complete the observations of the nebula, and then take the standard star observations.
- Use autodarks for images of arclamps, standard stars, and flat-fields. Do not use autodarks for your science exposures; instead, take a series of dark frames with the appropriate exposure time(s) after your observations.

4. Data acquisition steps

1. Review the table of spectral lines you will observe. How will you split them up in into wavelength ranges? Use the known arc lamp lines to plan how you will set the wavelength range (e.g. placing the Neon 5400Åline near the red edge of the spectrum seen in the CCD yields a wavelength range of 4700 - 5400 Å).
2. Assemble the spectrograph with the 20mm eyepiece viewing the spectrum.
3. Attach the Neon arc lamp.
4. Focus the spectrograph.
5. Change the grating angle so that you can see the bright yellow Neon line at 5852.48A (all other bright Neon lines are redder).
6. Exchange the 20mm eyepiece for the CCD camera.
7. Focus the camera on the arc lines. Adjust the camera so that the spectrum runs along the long axis of the CCD (i.e. horizontally). The arc lines should run exactly parallel to the short axis of the CCD.
8. After focusing, change the binning to bin in the spatial direction by a factor of 2. Do not bin in the spectral dimension.
9. Take an image of the Neon spectrum and identify the lines (use ds9's "projection" region to get a cut across the spectrum). What's the wavelength range along the long axis of the CCD?
10. Change the grating angle to your reddest wavelength setting. Take an exposure, making sure that no line is saturated.
11. Assemble the Autoguider camera as a slitviewer. To do so, remove the two black extension tubes of the slit-viewing assembly from the lens. Screw the remaining piece holding the lens into the black extension tube of the Autoguider camera.
12. Attach the Autoguider to the slitviewing port and focus it on the slits (turn on the slit illuminating lamp). Rotate it to that the slits are horizontal - this provides the largest field of view.
13. Remove the arc lamp.
14. Slew the telescope to your spectrophotometric standard star.
15. Attach the spectrograph.

16. Focus the telescope. Use the Autoguider to monitor the shape of the star. If the telescope is very out-of-focus, focus with the primary mirror's focusing knob first; then do a fine focus with the hand panel.
17. Adjust the telescope pointing so that the bright star is close to the center slit.
18. Check and if necessary, adjust, the finderscope pointing.
19. Sync the telescope to the position of the star (hold the `Enter` button for two seconds, press `Enter` again).
20. Re-take the arc lamp exposures by shining the arc lamp into the primary mirror. This is necessary to check whether the grating angle shifted when attaching the spectrograph to the telescope.
21. Move the telescope to place the star onto your target slit. Record a spectrum. Try to get 5000-20000 counts in the brightest individual pixels.
22. Take a flat-field: move the dome in front of the telescope; turn on the dome lights, record a spectrum. Try to get 20000 counts per pixel.
23. Go to your target.
24. Move your target onto the widest slit; take a 2 min exposure. Use the hand panel with a slow slew speed to keep your target at the same position on the slit. About half of the slit should be on our object, and the other half on empty sky.
25. Can you see all the emission lines you are targeting with this wavelength bracket in the 2-minute exposure? If so, take 4 more image for a total exposure time of 10 minutes. If not, take 14 more images for a total exposure time of 30 minutes. Make sure your target stays in the same position on the slit.
26. While shining the arc lamp into the primary mirror, change the grating angle to the next position. Make sure to record an arc lamp image. If the Neon lamp does not provide enough emission lines to cover the entire spectrum, also record an arc image of the Mercury lamp. Make sure no line is saturated.
27. Repeat the above steps to record the spectra at all wavelength settings.
28. If the telescope's pointing is inaccurate, first complete the observations of the nebula. Note the positions of bright emission lines in the arc spectra so that you can closely re-create the same grating settings when observing the standard star.
29. If your wavelength brackets do not overlap, record the spectrum of the spectrophotometric standard star also at intermediate settings to make sure you can reconstruct a contiguous spectrum. Make sure to record arc lamps, as well.
30. Finally, take a series of dark frames of the same exposure time(s) as used in your science images.

5. Data reduction steps

1. Create a master dark at each exposure time and subtract it from the corresponding spectra.

2. For each wavelength bracket, do the following:
   (a) Extract the spectrum of the nebula. Refer to the *Data reduction of long-slit spectra using* `pyraf` guide for details. If your exposures are well guided, you can combine invididual exposures prior to extraction. If the autoguiding did not work, you need to first extract the individual spectra, and average the results (you can use `numpy` or the `pyraf` task `scombine` to do so).
   (b) Find the dispersion relation (the pixel to wavelength mapping) from the arc lamp spectrum.
   (c) Identify the emission lines of the nebula. If your arc lines only cover part of the wavelength range, use the nebular lines to improve your wavelength calibration. The easiest way to do this is to add your science spectrum and your arc spectrum, with a rescaling to make them both visible at the same time.
3. Also extract the spectrum of the standard star at all wavelength settings, and calibrate the dispersion relation for each.
4. Derive the sensitivity function for each setting.
5. Combine the sensitivity functions into one sensitivity function that captures the sensitivity over the entire wavelength range of your observations. You should take into account aperture effects, i.e. that the exposures of the standard star capture different fractions of the total flux. You can assume that the throughput of the spectrograph as function of wavelength is independent of the central wavelength setting. Thus, your sensitivity function should be continuous, without steps between the different settings. If this is not the case, rescale them accordingly.
6. Apply the sensitivity function to the spectrum of the nebula.

6. Data analysis

- Identify which lines you can detect. Which lines were you expecting, but did not detect? Which lines that are not listed above can you identify? Measure the emission line strengths (e.g. using the `splot` routine in `pyraf`; smoothing may be helpful in bringing out lines). Determine upper limits for undetected lines.
- Measure the line ratios Hα/Hβ and Hγ/Hβ. Compare the results to tabulated values for case A and B recombination (e.g. Tables 4.1, 4.2, and 4.4. in Osterbrock 2005). Note how little these ratios change with with temperature and density. Instead, Hα/Hβ is used as an indicator for extinction along the line-of-sight. Do you have evidence of significant extinction towards your nebula?
- Measure the abundance of Helium relative to Hydrogen, and compare it the abundances in the Sun and other nebulae (e.g. Tables 5.3 and 10.2 in Osterbrock & Farland 2005). For the measurement, sum up the contributions from all detected lines. Can you measure abundances for additional elements?

- Determine the gas temperature from the [N II] lines, and/or from the [O III] lines. Temperature-sensitive indicators include the line ratios:

$$(\mathrm{F}(6548) + \mathrm{F}(6583)) \,/\, \mathrm{F}(5755) \quad - \quad \text{from [NII]} \tag{1}$$
$$(\mathrm{F}(4959) + \mathrm{F}(5007)) \,/\, \mathrm{F}(4363) \quad - \quad \text{from [OIII]} \tag{2}$$

  Refer to Chapter 5.2 in Osterbrock & Farland (2005) on how to estimate the gas temperature from these line ratios. Assume the standard low-limit density.
- Determine the electron density of the gas from the [S II] lines and, if you can, from the [O II] lines. Density-sensitive ratios include:

$$\mathrm{F}(6716)/\mathrm{F}(6731) \quad - \quad \text{from [SII]} \tag{3}$$
$$\mathrm{F}(3729)/\mathrm{F}(3726) \quad - \quad \text{from [OII]} \tag{4}$$

  Refer to Chapter 5.6 in Osterbrock & Farland (2005), in particular Fig. 5.8, on how to estimate the gas density from these line ratios. Is it consistent with the density assumed for the temperature estimate?
- Compare your measurements to results reported in the literature. Are they consistent? If not, what might be the reasons?

7. Lab report

The general instructions for the reports apply. Make sure to include

- A discussion of the type of the nebula you targets, why its spectrum is purely emission lines, and why certain line ratios are sensitive to the gas temperature and/or density.
- Keep track of your data reduction steps. Keep a (cleaned) version of this file up-to-date on github.
- Document your data reduction steps with figures / screenshots.

The timeline for the lab report, and intermediate check-ins is the following:

+1 week: Send in the extracted, wavelength-calibrated, and exposure-averaged spectrum for each wavelength setting.

+2 weeks: Send in your total sensitivity function and the flux-calibrated spectrum of the nebula. Also send in a table of measured emission line strengths.

+3 weeks: Report your estimates of line ratios, extinction, gas temperature and density, as well as literature-reported values. Present an initial assessment / interpretation of any discrepancies. Prepare an outline of your lab report.

+4 weeks: Hand in your lab report. Make sure that your analysis codes are attached to your report, or available on github.