

Planetary Nebula Term Project

Ay 102

January 12, 2020

The project will be due at the end of the term, but it is advisable to do a little each week in order to spread out the workload. It is called a ‘term project’ for a reason!

The main goal of the exercise is to analyze the optical spectrum of a planetary nebula (PN). Along the way, you will practice:

- identifying spectral lines,
- some basic spectral reduction and analysis (continuum subtraction, de-reddening, and emission line flux measurement),
- constraining physical properties (temperature, density, ionization state) from emission line fluxes

You will likely find that some of the code developed for your Ay101 PS4+PS5 can be adapted to tasks you are asked to perform here, eg continuum fitting and line measurement.

We’ll be studying several bright planetary nebulae. Deep HST images (Figure 1) show that these PNe have complex morphology.

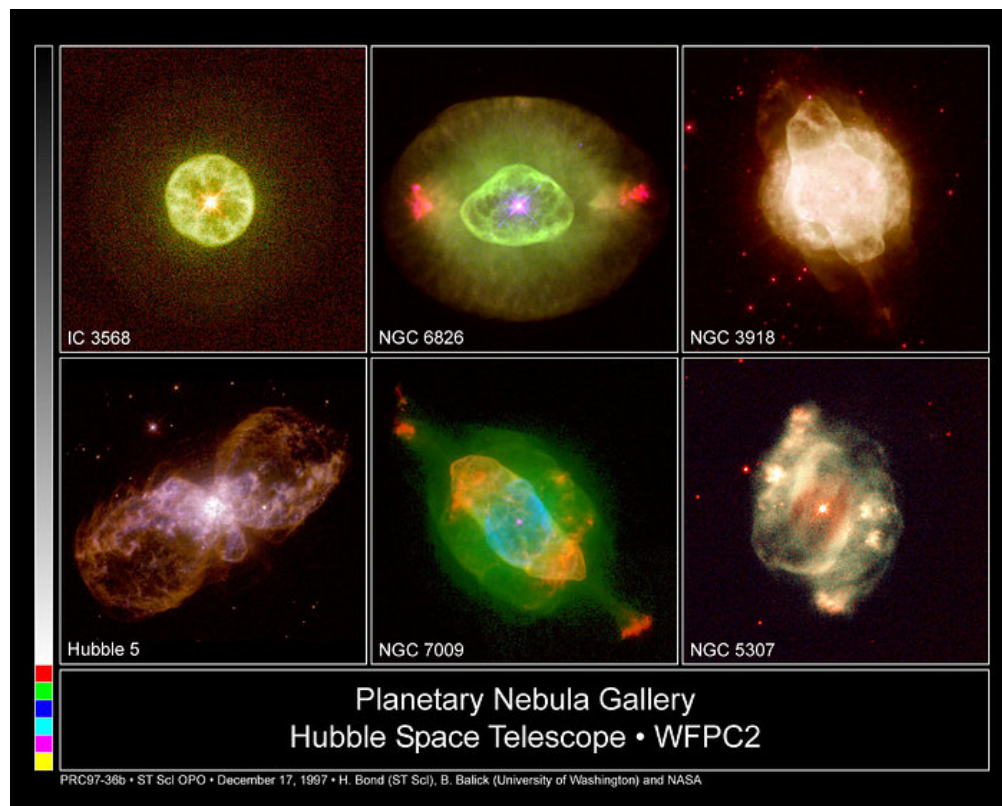


Figure 1: A small gallery of various planetary nebulae taken by the Hubble Space Telescope. Credit: H. Bond (ST ScI), B. Balick (University of Washington) and NASA/ESA.

Week 1-2

Read and summarize essential concepts of PNe

Read the introductory material located at¹ http://www.astro.caltech.edu/~lah/ay102/project/Salas_2003_PhDintro.pdf. Alternatively, consider the more advanced material in the review article² *Nebular Spectroscopy: A Guide on HII Regions and Planetary Nebulae* at http://www.astro.caltech.edu/~lah/ay102/project/Peimbert_2017_PASP.pdf. Answer the following questions in concise sentences:

1. **(1 pt)** What type of stars, in which evolutionary stage, evolve into PNe?
2. **(1 pt)** What are the typical temperatures of the central stars of PNe and of the PNe themselves?
3. **(2 pts)** What are the radiation mechanisms that produce the *emission lines* in PNe spectra? What are the radiation mechanisms that produce the weak *continuum* in PNe spectra?
4. **((1+1+1+2)=5 pts)** In Section 3.4 of the Peimbert article, it is mentioned that *ions with ground-state electronic configurations of s^2p^2 , s^2p^3 , and s^2p^4 are easily observed*.
 - (a) Write down two ions that are abundant in PNe with $1s^22s^22p^2$ configuration.
 - (b) Use angular momentum addition and symmetry properties required by Pauli's principle to predict the spectroscopic terms of p^2 configuration.
 - (c) Use Hund's rules to predict the ground level of p^2 configuration.
 - (d) Write down transitions commonly seen in PNe between these terms. Refer to the NIST atomic spectra database https://physics.nist.gov/PhysRefData/ASD/lines_form.html, look up the *air* wavelengths of these forbidden lines, and report your findings to 5 significant figures.

(bonus 5 pts) Answer the above questions (a)–(d) for the $1s^22s^22p^3$ and $1s^22s^22p^4$ configurations. You can also read Draine's Chapter 18 for enlightenment.
5. **(2 pts)** Among the collisionally excited lines mentioned in the articles, or that you wrote down in the previous question, name some pairs of lines that can be used to determine electron temperatures? How about electron densities?

¹Original full PhD thesis by Salas 2003: <https://www.rug.nl/research/portal/files/3022435/thesis.pdf>.

²Peimbert et al. 2017, PASP, 129, 082001

Week 3

Examine the spectral features of a PN

Let us first work with data on NGC 7027.

1. **(3 pts)** Acquire and plot the spectrum of NGC 7027.

Download from <http://www.astro.caltech.edu/~lah/ay102/project/NGC7027.csv>. The 'x' column is wavelength λ in the unit of angstrom, and the 'y' column is flux f_λ in the unit of $\text{ergs cm}^{-2} \text{s}^{-1} \text{Angstrom}^{-1}$. Plot the spectrum (*please make sure to put correct units on your axes!*) at suitably expanded scales. Some telluric lines or instrumental artifacts may be present.

2. **(2 pts)** Do you detect any absorption lines? If so, what might they be due to?
3. **(5 pts)** Label as many emission and absorption lines as you can, noting that some lines may be blended.

Here's one list of common PN emission lines: <https://web.williams.edu/Astronomy/research/PN/nebulae/legend.php>.

Week 4

Continuum normalization and flux measurements

Examine the large-scale continuum features. You already know about the radiation processes that produce the continuum from previous reading.

(10 pts) Write some code (in a language of your choice) to normalize the spectrum to the local continuum. There are many ways to do this, but here are some examples:

- **Easiest version** Measure the average flux in the wavelength region(s) around the emission line in question. Subtract this value from all the points in the emission line.
- **Easier version (1 bonus pt)** Measure fluxes in the wavelength regions to the left and to the right of the emission line in question. Fit a function (a line or second-order polynomial) to these two regions, and subtract the fit from the emission line.
- **Harder version (3 bonus pts)** This method (or some variant of it) is often better to use in cases where the spectral lines aren't as strong. Mask out all emission lines, then fit the rest of the spectrum with a function (a cubic spline with nodes every few 100 Å is usually fine). Subtract the fit from the observed spectrum.

Week 5

(10 pts) Write code to measure the total flux in the lines that you've just continuum-normalized. Using your code, measure the flux of H β and H γ (net fluxes above continuum). Here are some examples of how to do this:

- **Easier version** Just add up all the fluxes within the line. Pay attention to the units! We want total flux λf_λ , not just f_λ .
- **Harder version (bonus 2 pts)** Fit a line profile (a Gaussian should probably work fine) to the line, then integrate that. Again, make sure to watch the units!

Week 6

De-reddening

We actually have to de-redden our spectrum in order for our line measurements to make physical sense.

If you are programming in python, you can use the `extinction`³ python package. You'll need the standard Galactic reddening curve: Cardelli, Clayton & Mathis et al. (1989, hereafter CCM89) extinction function with $R_V = 3.1$.

If you do not use python, you can invoke a simple linear or quadratic reddening law. Please check with the TA for guidance.

See Section 21.1 of Draine if you need more than the class notes on reddening and extinction.

1. **(3 pts)** Compare your measured H β /H γ ratio with the theoretical expectation for a PN⁴. What is the reddening $E(B - V)$? Hint: use the standard Galactic curve to get the relationship between $E(B - V)$ and $A_{H\gamma} - A_{H\beta}$.
2. **(7 pts)** Correct the spectrum for reddening using $E(B - V)$. (Hint: again, use the standard Galactic curve to get the relationship between $E(B - V)$ and A_λ for all λ). Plot the original spectrum and the de-reddened spectrum on the same axes. Save the de-reddened spectrum as you will need it for the rest of the project.
3. **(bonus 2 pts)** Investigate the difference between the $R_V = 3.1$ "standard" extinction law and others representing different grain size distributions. Look at a shallower $R_V = 2.1$ and a steeper $R_V = 4$ extinction law. Which of the three has the strongest 2175Å feature? Which has the largest average dust grain size?

³<https://extinction.readthedocs.io/en/latest/>

⁴H β /H γ \approx 2.13 for $T \sim 10^4$ K, assuming Case B recombination (see, e.g., Osterbrock & Ferland).

Week 7

Measuring emission lines

(10 pts) Using your code from earlier, measure all of the emission line fluxes in the *de-reddened spectrum* and make a table of line ratios relative to $H\beta$.

Week 8

Measuring properties using emission lines

Remembering your answers from Week 1–2, we can now use nebular emission line ratios to measure actual physical properties! You can use the plots in Chapter 18 of Draine to estimate the physical properties described below.

1. (5 pts) Determine an approximate temperature for the gas, using appropriate line ratios. Hint: use Figure 18.2 of Draine.
2. (5 pts) Determine an approximate density for the gas, using appropriate line ratios. Hint: use Figure 18.4 of Draine.
3. (3 pts) Explain how you would measure elemental abundances, using emission line fluxes.

Week 9

Emission Lines and Central Star Temperature

(5 pts) The central stars of NGC 7027 and IC 3568 (download from <http://www.astro.caltech.edu/~lah/ay102/project/IC3568.csv>) have very different temperatures. Examine the spectra of each nebula and by noticing the presence or absence of certain emission lines, determine which one has a central star of higher temperature.

Hint: you can use lines in the following Table.

Wavelength (\AA)	Ion	Ionization Potential of next lowest ionization state
6087	[Ca V]	67.1 eV
7005	[Ar V]	59.8 eV
6434	[Ar V]	59.8 eV
6101	[K IV]	45.7 eV
8046	[Cl IV]	39.6 eV
7531	[Cl IV]	39.6 eV