**Problem Set 1**
ISM/IGM G6002y_2024
Issued: 02/08/24
Due: 02/19/24

Name:
Collaborated with:

**Photoionized Nebulae and Nebular Modeling with Cloudy**

In this problem set you will model a set of four examples discussed in class and in PIIM (Draine). They will build on the same model structure, but you will progressively make changes to the model, or explore a range of model parameters.

You will need to have a working version of Cloudy (c23.01) and it is highly recommended that you use pyCloudy as an interface for building the Cloudy input model and, most usefully, reading in the Cloudy outputs. A python notebook G6002_2024_PS1_Cloudy.ipynb provides a starting point for Problem 1 (plus other useful plots), and modifications will be required to do problems 2-4. It is similar to the example 1 code of pyCloudy.

It is fine to collaborate in groups, but turn in your problem set (answers, code and plots) individually. Most important is that by the end of the assignment, you feel able to build and analyze a model on your own, understand the inputs and outputs, and the code with which you are working. If you have any questions, send them by email to Prof. Schiminovich. We can also meet outside of class to address any questions, issues, debug codes, etc. (or stop by office anytime if door is open).

1. **Canonical Strömgren Sphere**

Start with the reference Strömgren sphere in the Python notebook, setting T and $Q_0$ for that of an O7V star (from Draine Table 15.1), log n = 3, and use the provided abundance table, metallicity = 1 (solar) and other parameter settings (e.g. rmin).

   a. Compare the radius of the H-ionized region to the Strömgren radius (Eq. 15.2)
   b. Compare the "width" (e.g. 0.9 to 0.1 ionization fraction) of the $H^+$ to $H_0$ transition in the Cloudy simulation to the mean free path of an ~18 eV photon in neutral hydrogen (Eq. 15.5). How many mean free paths is this width? Why might the Cloudy width be more or less sharp than the mfp?
   c. How many He-ionization zones do you see in your model? What is the approximate ratio of their radii, to the radius of the H-ionized region (e.g. $R(He^+)/R(H^+)$)? How does this compare to the expectation from the analytic ratio calculated in PIIM (Eq. 15.36)?

2. **Electron density diagnostics**

   Use this same example to study the dependence of emission-line ratios vs. electron density ($n_e$) for a range of densities log $n_e$ ~ 1, 2, 3, 4, 5. There are a few different ways to produce outputs to cover this $n_e$ range. You will find a range of electron densities within a single Strömgren sphere simulation, because the density strongly varies at the edge. However, it is easiest and better to produce different model outputs for an array of log $n_H$, since the sphere will be mostly ionized log $n_e$ ~ log $n_H$ over most of the region.

   a. Plot the ratio of the emissivities vs. log $n_e$ for key three-level atom density diagnostic lines from the $2p^3$ ions OII and SII (see Section 18.1.2 and 18.2 PIIM and Figure 18.4).

b. What are the ratios for the low and high density regime? What is the approximate 'crossover' density. Compare the Cloudy results to the analytic prediction for the line ratios in PIIM in the low density and high density regimes. Additionally, how does the crossover density compare with the critical densities for the ions and their relevant energy levels (see Table 18.2)?
c. How different are OII and SII as density diagnostics? If you were planning an observation, do you think you would need both? Also, what is their useful density range: e.g. would you use them to probe the density of a gas cloud with log $n_H \sim 1$?

3. **High-z (low metallicity) HII region and Temperature diagnostics**

Using your canonical Strömgren sphere in Problem 1 as a starting point, model how the properties of this HII region vary with metallicity, capturing a range that includes what we might be observing at high-redshift with JWST.

a. Vary the "metals" parameter to cover a range of metallicities from 3, 1, 0.1, 0.01, 0.001 (you can use linear units here) and produce five different model outputs.
b. Output the total line emissivities, and also generate a plot of the diffuse spectrum (using the provided example). Which emission lines dominate the emissivity in each case?
c. How do three key parameters of the HII region vary with metallicity? (Electron temperature $T_e$, $n_e$, $R_{S0}$)? (Does the $R_{S0}$ follow the expected variation in Eq. 15.3)?
d. Plot the temperature-sensitive emission line ratios for OIII and NII ($2p^2$ atom) key three-level transitions (see Section 18.1 PIIM and Figure 18.1 and 18.2). Would you conclude that these probes are also sensitive to metallicity?
e. <u>Why does</u> the electron temperature of the HII region vary with metallicity (all else kept constant)?

4. **Modeling the BPT diagnostic diagram**

Consider the Baldwin et al. 1981 "BPT" diagram that we discussed in class and in PIIM Section 18.7, and Figure 18.7. This is slightly more open-ended modeling problem.

a. Initially, simply make a "BPT" diagram using the relevant line ratios from your canonical model. Because this canonical HII region contains multiple zones of ionization, line ratios will span an interesting range. Which types of objects in the BPT diagram are most similar to the HII region?
b. Read PIIM Section 18.7 and think about how you might model the different regimes of the BPT diagram (star-forming galaxies, LINERs and Seyferts). Generate distinct models that aim to produce outputs in the different parts of the diagram. Note that you can use the Cloudy test suite for inspiration, and definitely feel free to discuss with others in the class and prof.
c. Produce your best version of Figure 18.7, using Cloudy outputs from different models (and overplotting eq 18.14)