Midterm (Take Home) - Astronomy 6002y

Prof. David Schiminovich

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1 Ionization and Heating of the IGM

A. Assume a model IGM with 1) baryon number density based on WMAP cosmology; 2) expansion evolution $n(z) = n_0(1+z)^3$; 3) uniform density at each z; 4) standard H and He composition (no other metals); 5) a post-H I reionization $T \sim 2 \times 10^4$ K. The IGM is exposed to a spatially uniform photo-ionizing radiation field described by the equations below, which provide the photoionization rate per particle based on the empirical formula taken from Haardt & Madau (1996)[1]:

$$\Gamma_{HI} = 6.7 \times 10^{-13}(1+z)^{0.73} \exp(-\frac{(z-2.30)^2}{1.90}) \;\; \mathrm{s}^{-1}$$

$$\Gamma_{HeII} = 0.01 * \Gamma_{HI}$$

Use the balance between photoionization and recombination to calculate and plot the evolution in the H I and He II fraction (x_{HI} and x_{HeII}) from z=8 to z=0. For simplicity, assume that He I is reionized at the same time as H I. At what redshifts do H I and He II become re-ionized (e.g. x_{HI} and x_{HeII} below 1%)?

B. Consider an idealized case where the ionizing spectrum comes mainly from AGN with $J(\nu) \propto \nu^{-1.2}$, both above and below the He II ionization energy, but with a spectral break at the He II ionization energy as implied by the equations above. Calculate the heating rate per particle for H I and He II photo-ionizations. Write down any simplifying assumptions that you make.

C. Plot the heating rate per unit volume for both H I and He II re-ionizations. Are He II photoionizations important for heating the IGM? If so, over what redshift range?

D. Absent any other source of heating, what process dominates the thermal evolution of the IGM at late times (e.g. low redshifts)?

E. One possible additional source of heating and ionization is via collisions. What is the evidence to suggest that the IGM (traced by Lyα absorption lines) is not collisionally ionized?

F. Describe qualitatively the effect that photoionization has on the 21-cm spin flip brightness temperature over the redshift range $8 < z < 20$. In your discussion be sure to separate the effect of heating vs. ionization on the expected 21-cm signal.

[1] Note that this fit becomes quite inaccurate at z>5, but we will ignore for this problem. Also the assumed cosmology is slightly different for these formulae.

2 Grain properties and steady state temperature

a. If extinction were to vary as a power law, A$\propto \nu^{\beta}$, what power-law index β would give $R_V = 3.1$?

b. Briefly describe (in words and equations as needed) why we find different dependencies on the steady state grain temperature for silicate vs. graphite grains (e.g. 24.19, 24.20).

   Describe how those equations were derived from Eq. 24.12, what assumptions were made (e.g. interstellar radiation field, grain absorption cross section) and how quantities based on the assumptions were determined.

c. If we consider dust illuminated by a central heating source of radius R, then we can rewrite the steady state grain temperature equation (24.17) as a function of normalized distance r/R:

$$4\pi a^2 < Q_{abs} >_{T_{SS}} \sigma T_{ss}^4 = \pi a^2 < Q_{abs} >_\star (4\pi J_\star) \left(\frac{R}{r}\right)^2$$

   By analogy with the derivation in sections 24.1.3-4 and eq. 24.18, derive an expression for the steady state temperature T_{SS} as a function of r/R (as well as β, ν_0, $J_\star$, etc). (You can assume that the central source has the same spectral shape as the ISRF).

   When $\beta = 2$, how does the dust temperature increase or decrease with radius?

d. If we observe T=50K thermal blackbody emission from carbonaceous grains illuminated by the ISRF, what size grains are we probably observing? Why?

   Do we expect any other emission signatures (non-blackbody) from these grains?

3 Ionization and Diagnostics of Photoionized Regions

Your midterm pyCloudy file: `G6002y_pyCloudy_Midterm.ipynb` has as its default a model of an H II region surrounding a central point source star. The initial values set density $n_H = 10^3$ cm^{-3} (`dens = 3`, log unit), solar metallicity (`'metals 1.0 linear'` in the options list), and the approximate effective temperature and H-ionizing photon production rate of a giant O6.5III star (`Teff = 37130`) and (`qH=49.23`, log unit).

Begin by running the model and inspecting all of the plots that have been generated. If these are all printing out fine then proceed to the following list of questions. Note that you should probably read through all parts of this problem first, as you may want to work on parts a-e in parallel as you vary model inputs at least three times. There are many parts/questions below, but you should write no more than 1 paragraph for each item, also showing calculations when needed.

a. **Strömgren spheres**: Pick 3-5 types/classes of O stars in Table 15.1 (make them different, to cover a range from O3V to O9I) and run the PyCloudy model, changing the blackbody temperature (`Teff`) and the value for QH (`qH`, log unit). What radii are calculated for the edges of the H II regions (e.g. where x_{HI} >0.1?) Calculate the Strömgren radius for each of these and compare with your Cloudy results. Do they agree? Why or why not?

b. **Radii of He II vs H II zones**: For the models above, calculate the ratio of the radii of the H II and He II regions (e.g. R(He^+)/R(H^+)). Compare with expectations calculated from Eq. 15.36.

c. **Temperature diagnostics**: Inspect the list of total emissivities for various lines. One critical ratio uses the temperature-sensitive 4363Å and 5007Å lines for O III, which is given in `O__3__5007A` and `TOTL__4363A` in the table. Compare the ratio of the emissivities of these lines with the expected electron temperature, based on Figure 18.2. Does this match the average electron temperature measured across the nebula?

d. **Density diagnostics**: This plot shows the ratio S II 6176Å/S II 6731Å, a commonly used electron density diagnostic. In what part of the H II/H I region does the electron density vary dramatically? Calculate the low and high density limits of this ratio using Eq. 18.5 and 18.6. and determine the critical density/transition point. Do the cloudy predictions fall in between these predictions?

e. **BPT diagram and 'zones' of N II and O III emissivity**: The final plot is the BPT diagram discussed in section 18.7. For the full range of O stars that you've modeled, describe how much emissivity is coming out in the O III vs. N II lines, and how the width of the emissivity zones varies. Compare the BPT diagram for this single nebula with the plots shown in the text, which are usually generated from line ratios in spectra of entire galaxies (Figure 18.7).

   To determine how the nebular line ratios change from run to run, track the 80% radius (color orange/red), which roughly corresponds to the half-volume radius of the nebula. For what type of central point sources will the half-volume radius lie on the upper, horizontal leg of the BPT diagram galaxy "locus" and when does it lie on the lower, vertical leg of the diagram? Speculate on how one might interpret this result and apply it to the observations of entire galaxies.

f. **Metallicity variations**: Using the initial default settings for the central point source, vary the metallicity by changing metals to 0.3, 0.1, 0.01 (e.g. `'metals 0.3 linear'`. What impact does changing the metallicity have on the physical properties of the nebula, specifically the electron temperature? Explain how and why the temperature varies with metallicity. Is this variation also reflected in the temperature diagnostic and emissivities discussed above?