PROBLEM SET CARBON, ASTRONOMY 216
"ALL ABOUT CARBON"

CII is the primary coolant in the diffuse atomic ISM, and shares its importance with OI in the atomic portions of PDR's. This problem is oriented towards understanding this coolant in some detail. In particular, we have our eye on two application to the atomic diffuse ISM:

(1) The "Cold Neutral Medium" (CNM) with $T \sim 50$ K of the diffuse atomic ISM. This is heated by grains and cooled by CII.

(2) "tiny-scale structure" (see Heiles 1997 ApJ, 491, 193 for a review). These are very small, but very dense HI structures embedded within cold clouds and are difficult to understand unless the temperatures are very much lower than the CNM. Accordingly, we will consider the possibilities of temperatures as low, even, as 10 K, which are usually not encountered in atomic portions of the ISM. At such temperatures, CI can become important.

1. We have asserted in class that any element having $IP < 13.6$ ev will be essentially all ionized in neutral regions. Show this for Carbon in cool regions having $T \lesssim 100$ K.

a. For the ionization equilibrium you need the recombination coefficient. For recombination coefficient, use two methods:

(1) Extrapolate H-recombination coefficients in Spitzer to low temperatures, using a "by eye" method (or something fancier if you prefer) to fit a power law to the tabulated values ($\alpha \propto T^x$). Here, should you use his ϕ_1 or ϕ_2?

(2) Look it up in a reference that considered it somewhat carefully. I used Morton (1975 ApJ 197, 85, Table 10). I'm sure you could find a more modern reference if you wanted to, but I'm not suggesting it.

You should find good agreement. Why can you neglect dielectronic recombination?

b. You also need ionization rates. For the ISRF, you can either use the blackbody approximation to the ISRF, the more accurate analytical expression of Draine (1978 ApJSuppl 36, 595, Fig 3 or equation 11), or Spitzer Table 5.5. For the photoionization cross section of Carbon, and all the other atomic parameters you need, use Hollenback and McKee (1989 ApJ 342, 306, tables in the appendix); or the references quoted by Spitzer page 117-118; or Genzel's article (for parameters other than the photoionization cross section).

c. Set up the equation for ionization equilibrium and solve it. Note that Carbon itself is the overwhelmingly large contributor of electrons for the heavy elements. Hydrogen contributes some because of ionization by cosmic rays, but we can usually neglect these (we will discuss later). In your formulation, assume Spitzer's cosmic abundance for C (4×10^{-4}) and include the depletion factor $\delta_{C,gr}$; also carry along G_0.

Express your result in two ways: first, using (n, T); second, by eliminating n in favor of

the pressure $\tilde{P} = \frac{P}{k}$. We like to express results in terms of pressure because one often imagines the thermal pressures among different phases to all be $\tilde{P} \sim 4000$ cm^{-3} K. As is clear from the fundamentals, the functional form of the T-dependence of the ratio $\frac{n(CI)}{n(CII)}$ is the same for all species; note how the CI increases at low temperatures.

Calculate numerical values for the ratio $\frac{n(CI)}{n(CII)}$ for $\tilde{P} = 4000$ cm^{-3} K and the two temperatures 10 and 100 K.

2. Calculate the ratio of the cooling rates for CI and CII. Assume low density, low optical depth conditions. Again, express the result both in terms of (n, T) and (P, T), and include δ and G_0.

3. Calculate the equilibrium temperature T_{eq} assuming heating is from grains as discussed in class and that C is the only coolant. The easy way to do this problem is to assume that only one ionization state dominates the cooling and the check to see that your assumption is correct. Again, carry along δ and G_0.

Express your result in terms of $\tilde{P}$. Note that you don't get a solution for all $\delta_{C,gr}\tilde{P}$!! And when you do get a solution, you get more than one!! (It's either feast or famine). Only one of these solutions is thermally stable; we discuss later.

4. Calculate the equilibrium temperature T_{eq} assuming that CII is responsible for both heating and cooling. That is, neglect photoelectric heating by grains and all other heating mechanism. Grain heating is, in fact, dominant in PDR's and most of the diffuse ISM; but for the application to tiny-scale structure, we have to reach low temperatures, and that can only occur if grain heating doesn't exist (like if they were destroyed by a fast shock). Note that this equilibrium temperature is almost independent of almost everything.

5. Calculate the equilibrium temperature T_{eq} including both CI and CII cooling. Draw a graph of T_{eq} versus n and, also, of $\tilde{P}_{eq}$ versus n. These graphical representations are the standard because they allow us to visually see whether gas is thermally stable (as we shall cover later in the course).

Recall that your calculation is for the low-density limit. Can CI cooling ever dominate CII cooling for $G_0 \sim 1$?