Ay 216: ALL ABOUT CARBON

1. INTRODUCTION

CII is the primary coolant in the CNM, although in warmer portions of the NM it shares its importance with OI. This problem is oriented towards understanding this coolant in some detail. There are two aspects of modern astronomy (maybe more?) for which you need to understand CII cooling details:

- Some CNM features have temperatures less than 20 K, and the conventional wisdom is that such low temperatures cannot be attained without molecular cooling. That's because the conventional astronomer doesn't appreciate diddley-squat about the importance of Carbon in shaping the thermal properties of the ISM.
- For $z \gtrsim 3$, the 158 μm line is redshifted into ALMA's observing window and typical galaxies should be fairly easy to detect. In fact, it should be the easiest way to detect high-z galaxies. Conventional wisdom is that, galactic-wide, the 158 μm line should come mainly from dense PDRs. Not necessarily! The CNM and, especially, the WIM can be equally important, or even dominant.

2. IONIZATION STATE OF CARBON

In class, we have asserted that any element having $IP < 13.6$ eV will be essentially all ionized in neutral regions. Show that this is true for Carbon in CNM regions that aren't too dense and aren't too dark. Recall that typical interstellar pressures are $\frac{P}{k} = \tilde{P} \sim 4000$ cm^{-3} K. In particular, find $n(CI)$, including its dependence on H-atom volume density (*not* C-atom!), depletion, temperature, and the G_0 factor for the ISRF. Express temperature as $T_2 = \frac{T}{100\ K}$, which is much more descriptive of the CNM than T in units of Kelvins.

To accomplish this, you need some numerical parameters...

1. The recombination coefficient for CII $\rightarrow$ CI. We need its temperature dependence for cold gas. You can obtain this by a rough fit to the values in Draine Table 14.6.
2. The ionization rates, which depend on the photoionization cross section (Draine, Figure 13.1) and the ISRF (In class, we used a diluted blackbody with $T = 10^4$ K; better is the fit given by Draine chapter 12.5, equation 12.7). What range of photon energy is relevant here? And how do you convert from energy density U to photon flux? (Shortcut: look at Draine Table 13.1!).

3. The abundance of *gaseous phase* Carbon relative to Hydrogen. This is normally taken as the standard Solar abundance (Draine Table 1.4) as modified by depletion onto grains (Draine Table 9.5).

4. The electron density. Where do the electrons come from? Not from Hydrogen—which contributes some electrons from cosmic-ray ionization, but not many (we will discuss later).

3. CARBON HEATING RATE

Calculate the approximate Carbon photoionization heating rate in an HI region, which arises from the kinetic energy of the ionized electron when CI is ionized. Express the rates in terms of n(H) and temperature T_2—and *not* n(CII).

If you can answer this question, then you understand what's going on. The question is: *"Why is the heating rate independent of G_0, the intensity of the ISRF?"*

4. CARBON COOLING RATES

1. Calculate the CII cooling rates per CII ion (i.e., ergs ion^{-1} sec^{-1}) and also per unit volume (i.e., ergs cm^{-3} sec^{-1}). Assume low density, low optical depth conditions. Express the volumetric rates in terms of n(H) and temperature T_2—and *not* n(CII). We will want to look at the line emission from the CNM, the WNM, and the WIM, so we need cooling rates for CII collisions with HI and, also, electrons.

2. How valid is the 'low-density-limit' assumption in the CNM and WIM? To check this, determine the critical density for the transition for HI and, also, electrons. Getting the fundamental info is not so easy (unless you can figure out CLOUDY, I suppose). For the Einstein A, use the NIST data base `http://www.nist.gov/pml/data/asd.cfm` . For electron collisions, you need a collision strength; see Draine Appendix F. For neutrals it's not so easy. Draine gives the CII collisional rate in chapter 17.4. For a limited number of other atoms/ions, he gives critical densities in Table 17.1. A more comprehensive source is Hollenbach and McKee (1989 ApJ 342, 306, tables in the Appendix); it's older and less accurate, but at least for species other than C, O, and Si you get a number you can use!

5. THE 158 μm LINE FROM EXTERNAL GALAXIES

Suppose you are using ALMA to observe the 158 μm line from a high-z galaxy. Estimate the ratio of the line intensities contributed by the WIM and the CNM. For this estimate, assume equal masses of CNM and WIM (in the MW, in the Solar neighborhood, there is somewhat less CNM than WIM). Also assume that the thermal pressures are equal. Assume, also, that most of the line emission comes from the CNM and the WIM, not the much higher-density PDRs (I *think* this is the case, but I'm not sure. . .).

6. EQUILIBRIUM TEMPERATURES FOR THE CNM

For the CNM, calculate the equilibrium temperature T_{eq} assuming that Carbon is totally responsible for heating. That is, neglect photoelectric heating by grains and all other heating mechanisms. Grain heating is, in fact, dominant in PDRs and most of the diffuse ISM; but for the really cold cloud and maybe for tiny-scale structure, we have to reach low temperatures, and that can occur only if grain heating is negligible. Note that this equilibrium temperature is almost independent of almost everything.

You get a transcendental equation. You can solve it using fancy numerical techniques if you want. If I were you, though, I'd use use your noggin and make it easy.

7. EXTRA HEATING NEEDED!

Above, you should have found equilibrium temperatures in the neighborhood of 10-15 K. However, observed temperatures of the CNM are more typically 50 K. By what factor must the heating rate increase to achieve an equilibrium temperature of 50 K?

8. CARBON COOLING TIMESCALES

How long does it take for the CNM equilibrium temperature to be attained? The cooling timescale τ_{cool} is defined as

$$\frac{1}{\tau_{cool}} = \frac{d \ln \Delta T}{dt} = \frac{1}{\Delta T}\frac{d\Delta T}{dt} = \frac{2R_{cool}}{3k\Delta T} \tag{1}$$

where ΔT is the offset from the equilibrium temperature T_{eq} and R_{cool} is the net cooling, i.e. $R = n^2\Lambda - n\Gamma$. Is this long or short?