PROBLEM SET 11, ASTRONOMY 216
THE TIME DEPENDENT WNM?

This problem set explores, in a very superficial way, the degree to which thermal equilibrium and ionization equilibrium for the WNM is a reasonable idea. The WNM is subject to transient heating and ionization by SN shocks and, perhaps, gamma-ray bursts. If a SN shock is slow enough, $V \lesssim 20$ km s^{-1}, then the ionization of the shocked gas doesn't increase significantly but, because the pressure is high behind the shock, the cooling time becomes shorter than for the unperturbed WNM. If the shock produces significant ionization, then the cooling time decreases markedly and ionization equilibrium doesn't obtain. In either case, the WNM cools to CNM; conversion of WNM to CNM is a major point in the McKee/Ostriker ISM model. A gamma ray burst could produce similar effects, but without the compression associated with the shock.

1. Consider a packet of WNM that is in thermal and ionization equilibrtium at, say, 8000 K and at the standard interstellar thermal pressure $\tilde{P} = \frac{P}{k} = 4000$ cm^{-3} K.

a. What is the dominant cooling mechanism? Estimate the timescale for establishing thermal equilibrium, i.e. the cooling timescale.

b. Estimate the time between SN shocks if $Q = 0.5$. Compare with above.

2. Consider the same packet of WNM. It is exposed to a gamma-ray burst. Suppose that the burst ionizes everything to the state normally encountered in HII regions excited by an O star and heats the gas to 8000 K. After the pulse, the heating reverts to the usual sources for the NM. The gas will cool if photoelectric grain heating doesn't dominate the cooling. Does the gas cool? What is its approximate ionization fraction when it cools to a few hundred K?

Comments: With such an impulsive heating the initial temperature would undoubtedly be higher. However, because of collisional excitation of Lyα the cooling curve rises so steeply above 8000 K that we can assume that the temperature drops very rapidly to that point and begin our worries there. The ionization of heavy elements would probably be lots higher, too, but I wanted to make an illustrative calculation. What is the major coolant at first, when the gas is 8000 K? What happens when the temperature drops to something like 6000 K? (See cooling curves for HII regions in Spitzer or Osterbrock).

It's most appropriate to take cooling at constant pressure. In doing this, I assumed that the burst didn't compress the gas and I neglected the pressure increase from the doubling of particles upon ionization. During subsequent cooling, I assumed the total H-nuclei density to be inversely proportional to temperature, thus neglecting the extra pressure drop caused when the electrons and protons combine thus reducing the number density. And I assumed only one coolant below 6000 K and neglected its change in ionization (but not the change in n_e). And I took the Oxygen gaseous abundance equal to 331 parts per million relative to H; we will discuss the reason for this later, when we discuss cosmic abundances and depletions.

I did this numerically for fun, and also evaluated the timescales for cooling and recombination at T=6000 K (timescale for x equals the reciprocal of $\frac{d\ln x}{dt}$). The timescales aren't all that different, but because even a tiny bit of residual ionization makes a huge difference, we conclude that "recombination is slower than cooling".