Astronomy 501 Spring 2013
Problem Set #5

Due in class: Friday, Feb. 22
Total points: 7+0.5

1. **[2 points]** Rybicki & Lightman, Problem 5.1 Each part is worth 0.5 points.

2. **[0.5 points]** Rybicki & Lightman, Problem 4.2

3. **[1 point]** Rybicki & Lightman, Problem 4.7 Each part is worth 0.5 points.

4. *Bremsstrahlung Example: Galaxy Clusters.* Perseus is the most luminous galaxy cluster as seen in X-rays. An X-ray spectrum of Perseus, taken by the *INTEGRAL* spacecraft, appears in Eckert, D., & Paltani, S. 2009, *Astron. & Astrophys.*, 495, 415. Focus in particular Figure 5. As discussed in the paper, the emission contains several components. Here we will treat the cluster in a simplified way, as a single, uniform sphere radiating thermal bremsstrahlung with a single temperature T.

   (a) **[0.5 points]** From Figure 5, estimate the temperature kT of the cluster. Express your answer in keV and in Kelvin.

   Also estimate the integrated X-ray flux F from Perseus, in units of [keV cm^{-2} s^{-1}] and in [erg cm^{-2} s^{-1}].

   (b) **[0.5 points]** Assuming a thermally-averaged gaunt factor $g_{\rm ff} = 1$, find an expression for the integral emission coefficient for thermal bremsstrahlung at temperature T.

   (c) **[0.5 points]** Assume the cluster is a uniform sphere of fully ionized hydrogen, with gas mass $M_{\rm g}$, temperature T and radius R. Find an expression for the integral bremsstrahlung luminosity of the cluster, assuming it is optically thin. *Hint:* find express the proton and electron densities in terms of $M_{\rm g}$.

   (d) **[1 point]** Perseus has a radius $R \sim 0.5$ Mpc, and is at a distance $d \approx cz = 70$ Mpc. Using these values and the Perseus X-ray flux, estimate the mass of intracluster gas in Perseus. Express your answer in units of $M_\odot$.

   (e) **[1 point]** Estimate the optical depth of Perseus for *absorption* via bremsstrahlung, based on the gas mass you found. Is our optically thin assumption justified?

   (f) **[0.5 bonus points]** The galaxies in Perseus have a velocity spread ("dispersion") of $\sigma \sim 1300$ km/s. Using the Virial theorem, estimate the total mass $M_{\rm tot}$ in Perseus, expressing your answer in $M_\odot$. Compare your answer to the gas mass, and comment on any difference.