Astro 519A; Problem Set 4 – write a report on one radiative process

Due Dec 4 by 5pm (in McQuinn's mailbox). We will also have five minute presentations on Thursday, Dec 3, where everyone will present on their emission mechanism. These presentations will count towards the participation portion of your final grade. Everyone is asked to send a PDF with slides (2-4 slides) for their presentation by noon on Dec 3.

Write a ≈ 2 page discussion on a radiative process of relevance to an astronomical topic you are interested in and including references. It can either be a continuum emission or absorption process (e.g. dipole radiation, synchrotron, free-free, inverse Compton, dust, Thomson or Raleigh scattering) or a bound-bound or bound-free process (e.g. line emission, photoionization). Example topics could be synchrotron emission from radio quasars, water absorption in planetary atmospheres, CO emission from molecular clouds, Rayleigh scattering of the CMB, etc. (You are welcome to run your topic by me in advance.) When possible/applicable, answer the following:

- Is the radiation thermal or non-thermal? What is a typical optical depth? What are characteristic values for the intensity and flux? What does the emission/absorption reveal about the underlying state of the system (temperatures, energies, particle densities, etc)? Or how does it shape the properties of the system (cooling times, pressure, etc)? If there are numerical simulations of your process, what radiative transfer methods are used?
- for continuum processes: What range of wavelengths is this emission operating/observed? Are there features in the spectrum and what do they indicate about the source?
- for bound-bound emission and absorption: What is the Einstein A coefficient? What sets the line width?

Where possible, give simple formulae. The project will be graded out of 20, and 20/20 will be a project that goes beyond answering the above. Please do this project on your own.

Below is an example write-up.

bremsstrahlung from galaxy clusters

Clusters of galaxies are the largest virialized structures in the Universe, with masses that can exceed $10^{15}M_\odot$. They come into existence at relatively low redshift $z < 1$. Here we discuss how galaxy clusters are studied via their bremsstrahlung emission in the X-ray as well as how this emission affects the physical state of clusters. For our calculations, we take characteristic values for the density of galaxy clusters of $n = 10^{-4}\mathrm{cm}^{-3}$, size of $R \approx 500\mathrm{kpc}$, temperature of $T = 10^8\mathrm{K}$, redshift of $z = 0.2$ (corresponding to 1000 Mpc away), and age of $10\,\mathrm{Gyr}$ (see Kravtsov & Borgani 2012).

Cluster gas is likely to be in thermal equilibrium because the electron-ion equilibration timescale via Coulomb collisions is about 10^9yr for the fiducial specifications, less than the cluster age (and note that 10^8K is on the high side of cluster temperatures, with the equilibration time scaling at $T^{3/2}$).[1] Equilibrium simplifies the calculations, allowing us to use the equations of thermal bremsstrahlung from RL, chapter 5. The bremsstrahlung optical depth across a cluster is given by (RL 5.19b)

$$\begin{aligned} \tau_\nu^{ff} &= 2\times 10^{-42}\left(\frac{T}{10^8~\mathrm{K}}\right)^{-1/2}\left(\frac{R}{500~\mathrm{kpc}}\right)\left(\frac{n}{10^{-4}~\mathrm{cm}^{-3}}\right)^2\left(\frac{h\nu}{1~\mathrm{keV}}\right)^{-3}(1-e^{-h\nu/kT})\bar{g}_{ff}, \\ &\longrightarrow_{\mathrm{RJ~limit}} 300\left(\frac{T}{10^8~\mathrm{K}}\right)^{-3/2}\left(\frac{R}{500~\mathrm{kpc}}\right)\left(\frac{n}{10^{-4}~\mathrm{cm}^{-3}}\right)^2\nu^{-2}\,\bar{g}_{ff}, \end{aligned} \tag{1}$$

where we have taken $Z = 1$ (a good approximation for cluster gas that is primarily hydrogen). Thus, the gas becomes optically thick to free-free absorption at $\nu \lesssim 10\,\mathrm{Hz}$ – an unobservably small frequency (below the plasma frequency of the ISM of $\sim 10^5$ Hz and well below the plasma frequency of our atmosphere of $\sim 10^7$Hz; RL eqn. 8.12).

Since the optically thin limit holds, the specific intensity of cluster bremsstrahlung emission is (RL 514b)

$$I_\nu = \int_0^R ds j_\nu = 9\times 10^{-27}\left(\frac{T}{10^8~\mathrm{K}}\right)^{-1/2}\left(\frac{R}{500~\mathrm{kpc}}\right)\left(\frac{n}{10^{-4}~\mathrm{cm}^{-3}}\right)^2 e^{-h\nu/kT}g_{ff}(\nu)~\mathrm{erg~s^{-1}~cm^{-2}~Hz^{-1}~sr^{-1}}, \tag{2}$$

corresponding to a bolometric intensity of

$$I = \int d\nu I_\nu = 2\times 10^{-7}\left(\frac{T}{10^8~\mathrm{K}}\right)^{1/2}\left(\frac{R}{500~\mathrm{kpc}}\right)\left(\frac{n}{10^{-4}~\mathrm{cm}^{-3}}\right)^2\bar{g}_B~\mathrm{erg~s^{-1}~cm^{-2}~sr^{-1}}. \tag{3}$$

Most of the bolometric intensity falls at $h\nu \sim kT \sim 10keV$, in the X-ray band. In addition, the observed flux (ignoring redshifting which would add a factor of $(1+z)^{-4}$) is

$$F_\nu = \Delta\Omega I_\nu = 7\times 10^{-13}\left(\frac{R/d}{10^3}\right)^2\left(\frac{T}{10^8~\mathrm{K}}\right)^{1/2}\left(\frac{R}{500~\mathrm{kpc}}\right)\left(\frac{n}{10^{-4}~\mathrm{cm}^{-3}}\right)^2\bar{g}_B~~\mathrm{erg~s^{-1}~cm^{-2}} \tag{4}$$

The 5σ X-ray flux sensitivity of XMM-Newton – an X-ray telescope often used to survey clusters – is 10^{-14} erg s^{-1} cm^{-2} in 20 kilo-second (and most clusters reside at their sensitivity threshold – although our fiducial cluster would be a particularly large one).[2] Thus, our estimate for the flux is consistent with observed fluxes. Also note that the above top hat approximation for the density profile of a cluster is an underestimate as much of the flux comes from denser inner regions.

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[1] The electron-electron equilibration timescale is much shorter, but shocks (the heating source) are more efficient at heating the ions. In addition, plasma instabilities can result in faster equilibration. Cosmological simulations of clusters verify that equilibrium holds (Chièze et al. 1998).

[2] `http://xmm.esac.esa.int/external/xmm_science/x-ray-symposium/173736_gl_cluster.pdf`

Bremsstrahlung is the dominant emission process in the X-ray and is how galaxy clusters are typically detected. Because the emission scales as n^2, the center of clusters are much brighter than the outskirts. With Chandra and XMM, typically the emission is detected out to the distance where the cluster has a density that is 500 times the mean density, which tends to be a few hundred kpc, several times less than the cluster virial radius. The X-ray spectrum allows one to measure $\mathrm{EM} = \int ds n^2$ as well as T. Clusters are roughly in hydrostatic equilibrium such that $nVkT \sim GM^2/R$, where $V \sim R^3$ is the cluster volume and M is the cluster mass. Thus, measurements of the temperature and density can be used to model the enclosed cluster mass. This allows researchers to infer the mass function of clusters, and the cluster mass function is a cosmological probe because it is very sensitive to the primordial amplitude of density fluctuations in the Universe (Allen et al. 2011).

The cluster gas cooling timescale is

$$t_{\rm cool} = \frac{3/2 n k_b T}{dW/dtdV} = 500\,\mathrm{Gyr}\left(\frac{T}{10^8~\mathrm{K}}\right)^{1/2}\left(\frac{n}{10^{-4}~\mathrm{cm}^{-3}}\right)^{-1}\bar{g}_B^{-1} \tag{5}$$

where we have used eqn. 5.15B in RL. For our fiducial cluster parameters this is 50 times longer than the age of the cluster. This means that most of the gas in the cluster is not able to cool and condense (unlike in galactic halos where the cooling time is much shorter because of the temperature dependence of free-free cooling). Rather, clusters are characterized by a hot gaseous atmosphere, with galaxies that were formed prior to the cluster whizzing around. See Figure 1. Note the temperature dependence of the above formula means that for lower temperature gas (such as occurs in galactic halos), the cooling time is shorter than the system age, allowing galaxies to form!

However, in the cluster core the cooling time can be much shorter than the cluster lifetime (especially in "cooling core" clusters where a temperature decrease is seen towards the center of the cluster). This leads to the cooling flow problem – most numerical simulations of clusters find a large flow of gas (gas that has cooled and lost its pressure) towards the cluster center that is not observed. It is believed that feedback from the large black hole at the cluster center injects energy into surrounding gas, stabilizing accretion and preventing a cooling flow (Fabian 2012).

Allen, S. W., Evrard, A. E., & Mantz, A. B. 2011, ARA&A, 49, 409 Chièze, J.-P., Alimi, J.-M., & Teyssier, R. 1998, ApJ, 495, 630

Fabian, A. C. 2012, ARA&A, 50, 455

Kravtsov, A. V., & Borgani, S. 2012, ARAA, 50, 353

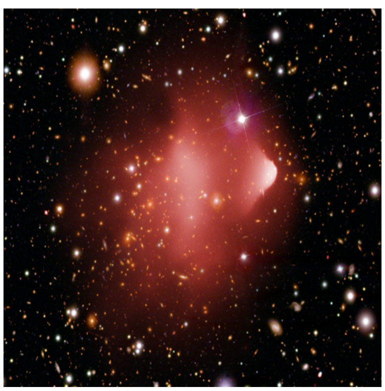

Fig. 1.— Image of one of the most famous clusters, the Bullet Cluster. Optical data is superimposed on Chandra X-ray (showing bremsstrahlung). A small cluster merged with a larger cluster leading to the "bullet", which is bremsstrahlung from denser and hotter shocked gas. This cluster is used to place some of the tightest constraints on the interaction cross section of the dark matter.