The role of Radiative Cooling Processes in Galaxy Formation

Juan Manuel Espejo

Galaxies are fascinating systems that constitute the built-in cells of the cosmos, and therefore our theories about their formation have to be consistent, robust, and must involve all important physical processes, with regard to baryonic and non-baryonic matter. It has long been known that gravitation is the leading force which controls and shapes the large scale structure of the Universe, as well as mainly responsible for the assembling of galaxies. Still, this force is not enough to explain how such macro-structures form as evidenced by observations. Thus, when it comes to describing their collapse, *radiative cooling processes* are keystones in the whole picture.

To set up the context, we have a system composed of two parts: one is non-dissipative dark matter and the other is baryonic gas. The latter can, in principle, collapse further. This does not occur however, due to the high virial temperature of the gas (i.e. $\rho \propto T$), which in turn creates pressure that counteracts the gravitational force directed inwards. In order to decrease the outwards pressure that prevents the system from collapsing, baryons must radiate some of their energy away. For this reason, it is essential to study the processes capable of heating or cooling the baryonic gas. We can start from quantifying how long the gas takes to lose its internal energy, using the *cooling time* defined as,

$$t_{\rm cool} = \left(\frac{E}{\dot{E}}\right) \propto \rho^{-1}. \tag{1}$$

Now, by comparing the above with other relevant time-scales of interest, such as the Hubble time t_H (age of the Universe) or the dynamical time $t_{\rm dyn}$ (also known as the free fall time), we have three important regimes:

1) $t_{\rm cool} > t_H$: Cooling is unimportant as it takes too long to be effective, i.e. more than the age of the Universe, so the latter expands without counterparts and no substantial collapse occurs. This is the regime of galaxy clusters, which we will discuss in further detail later.

2) $t_{\rm dyn} < t_{\rm cool} < t_H$: In this scenario cooling is possible, but free fall time can cause the gas cloud to readjust its density so that it remains in hydrostatic equilibrium, and therefore collapse stops. The overall effect is that gas will move along lines of constant M_J [1] in the ρ vs T diagram, towards higher densities and temperatures (recall that $M_J \propto \rho^{-1/2} T^{3/2}$). In short, the system does collapse, but barely so and too insufficiently to form a galaxy.

3) $t_{\rm cool} < t_{\rm dyn} < t_H$: This case, also known as catastrophic collapse, allows for energy to be efficiently radiated away from the system. In the limit $t_{\rm cool} \ll t_{\rm dyn}$, T will decrease at constant ρ (i.e. isochoric cooling) and cooling continues until a temperature for which $t_{\rm cool} = t_{\rm dyn}$ is reached. Thus, the Jeans mass drops very quickly and the system does not have time to re-adjust its density like it does in the second regime. With a consistently lower M_J, collapse can occur in smaller structures as well. Finally, the fragmentation will stop when $M \sim M_J$.

To complete the previous schemes, an important function must be introduced. Namely the cooling function, which quantifies the energy emitted per unit time and volume:

$$\Lambda(T, Z) \equiv \frac{\mathcal{C}}{n_{\rm H}^2} \tag{2}$$

In which case units are erg $\rm s^{-1} cm^{-3}$. As a side note, this last function depends on metallicity, but little presence of high Z elements will be found in the cooling process. The reason for this is that despite of the fact that hydrogen and helium are the most abundant elements of the interestellar medium, their cooling properties are not significant because electrons (of H and He) do not bear sufficient energy at low temperatures to induce

[1] here M_J is the Jeans mass, and it stands for the mass scale above which Jeans smoothing becomes unimportant and collapse may occur.

photon emission from tightly bounded electrons. In equation 2 $n_{\rm H}$ is the number density of hydrogen that includes the neutral and ionized contributions, and $\mathcal{C}$ is the volumetric cooling rate.

It should be emphasized that gas can radiate its energy away, while conserving its specific angular momentum (such that $t_{\rm cool} < t_{\rm dyn}$), within a region defined by a *cooling radius*, where $r < r_{\rm cool}$. An alternative definition states that this is the radius at which the cooling time equals the age of the Universe at a given redshift.

The intensive properties of the medium (i.e. T and ρ), define different types of cooling processes. As such, equation 1 shows that gas cools at higher rates in regions with higher density, where the number of interactions that release radiation increases. Then, the relevant radiative cooling processes discussed here result from collisions among particles, or in other words: they are two body interactions that lead to $\Lambda \propto n_1 n_2 \propto \rho^2$. For the sake of completeness we list the main radiative processes (with their corresponding reaction) in table 1 [4] [5].

Name	**Reaction**
1) Bremsstrahlung (Free-Free)	$e^- + X^+ \rightarrow \gamma + e^- + X^+$
2) Recombination (Free-Bound)	$e^- + X^+ \rightarrow X + \gamma$
3) Collisional Ionization (Bound-Free)	$e^- + X \rightarrow 2e^- + X^+$
4) Collisional excitation (Bound-Bound)	$e^- + X \rightarrow e^- + X$

Table 1: Main cooling processes involving collision of particles.

As all the reactions require electrons, cooling mechanisms are much more efficient after re-ionization. The exchange of momentum between particles engender a common characteristic for all of these processes, i.e. the loss of kinetic energy from one of the collisional particles, whereby a photon is emitted [5]:

1. **Bremsstrahlung (free-free):** When an electron is accelerated by a collision with an ion resulting in emission of photons. This process is called Bremmsstrahlung and has a continuum spectrum.
2. **Recombination (Free-Bound):** In this process a free electron recombines with an ion and, consequently, the binding and kinetic energy of the free electron are radiated through the emission of a photon. The recombination time is given by $t_{\rm rec} = (n_e \beta)^{-1}$ where β accounts for the recombination rate.
3. **Collisional Ionization (Bound-Free):** A bound state atom impacts on another particle (primarily an electron). Thus, this collision releases an initially bound electron which results in cooling the gas, as the free electron loses partially its kinetic energy.
4. **Collisional excitation (Bound-Bound):** For this scenario, a free electron collides with an atom, moving a bound electron to an excited state. When the excited electron decays back to its ground state, it does so by emitting a photon and cooling takes place.

From the study of ionic species that constrain the cooling function, one can show (see e.g. [4]) that ions are equally created and disrupted, and thus the system remains in an equilibrium known as **ionization equilibrium**. This is only possible if the time-scales of the discussed radiative processes are much shorter than the hydrodynamical time-scales of the gas. If such balance is reached without adding ionizing radiation to the equation, we call it collisional ionization equilibrium (CIE for short), and if the gas is in this state the cooling function can be easily determined. Fig. 1 shows the different cooling rates for a primordial gas which is in collisional equilibrium, and the respective shape of each individual process as will be discussed later, while Fig. 2 shows the cooling functions for solar abundances for a medium which is also in collisional equilibrium [3].

In addition to the above, we must briefly introduce the effect of photoionization heating because we cannot ignore the presence of radiation fields. In some cases, atoms are able to absorb photons, this is what we call photoionization. When this happens, the presence of an ionizing radiation field can change the population densities of ions, affecting the cooling rate of the gas. In static conditions, recombination can generally offset photoionization, which implies a balance between both, i.e. $n_{\rm HI}\Gamma = n_e n_{\rm HII}\beta$ (see Fig. 2, right panel), where the photoionization rate is defined as $\Gamma \equiv t_{\rm ion}^{-1}$ and is related to the intensity of the UV background radiation. However, when recombination occurs there is an energy loss that, nevertheless, is smaller than the gain from photoionization. The aftermath of these processes leads to something often called **photoionization heating**.

This heating process helped to partially explain the so called *overcooling problem* [2]. In the presence of heating sources, the cooling function becomes:

$$\Lambda(T, n_{\rm H}) \equiv \frac{\mathcal{C} - \mathcal{H}}{n_{\rm H}^2} \tag{3}$$

where $\mathcal{H}$ is the heating term. This net cooling rate is also a function of density because of the competition between photo-ionization and recombination. Since we have introduced the relevant time scales and radiative cooling processes we can move on to discuss their relevance in the different processes of galaxy and galaxy cluster formation in terms of three relevant temperature ranges.

- First, at high temperatures, namely $T > 10^7 K$, the gas is fully ionized and so the free-free cooling (i.e Bremsstrahlung) dominates. In this case $\Lambda \propto \rho^2 T^{1/2}$. Here if $t_{\rm cool} = t_{\rm dyn}$ then we have $\rho \propto T$.
- At intermediate temperatures, $10^4 K \leq T \leq 10^6 K$ for primordial abundances and $10^5 K \leq T \leq 10^7 K$ for solar abundances, collisional excitation (i.e. lines) dominates and the total radiative cooling rate scales roughly as $\Lambda \propto \rho^2 T^{-1/2}$, so in this case $\rho \propto T^3$.
- For $T < 10^4$K, collisions are not energetic enough to ionize atoms or even excite them out of the ground state, so the cooling rate basically drops to zero (see Figs. 1 and 2). The low temperature cut-off that we see in the cooling curve is set by the ionization cut-off of hydrogen.

There is an upper limit on galaxy masses (see Fig. 3) of around $M_{\rm vir} > 10^{12} M_\odot (z = 0)$ and $M_{\rm vir} > 10^{13} M_\odot (z = z_\odot)$ because the more massive the virialized halo, the bigger its virial temperatures and since more massive halos tend to collapse later, they have longer cooling times, which decreases the formation of stars and consequently the formation of a galaxy. In other words, more massive galaxies cannot form because they cannot efficiently cool their gas.

In the case of galaxy clusters, the rapid cooling of the intracluster medium creates a cooling flow associated with a change in pressure which subsequently creates an inwards flow of matter [6]. The timescale for cooling of the intracluster medium (ICM) is relatively short [7]. The ICM rapidly loses its energy by X-ray emission, which is proportionally correlated to the square of its density, which increases towards the centre. Additionally, the gas temperature drops by a factor of 3 or more. The short radiative cooling times and steep temperature drop are likely to be related, meaning that the low temperatures are caused by radiative cooling. Because of the high temperatures in the ICM, the cooling process which dominates is Bremsstrahlung. [8].

Finally, let us discuss the prominent features of the cooling curves, namely the peaks. The cooling functions for Bremsstrahlung, recombination and collisional ionization are smooth functions of temperature and do not present peaks. In the case of collisional excitation however, there is a limited range of energies given the nature of the process (electron transitioning between bound states). The collision between an electron and a positive ion gets the ion excited after the collision, it will deexcite and radiate the gained energy away. This process only occurs when the temperature is too high, and there are no bound transitions left. The peaks in the cooling function are therefore caused by collisionally excited electronic levels [3] as clearly seen in figures 1 and 2.

A question that pops up is how cooling processes, and consequently the cooling peaks that we observe, are affected by the existence of heavier elements, namely metals. In our attempt to approach this issue we will distinguish two regions of interest: $10^4 K < T < 10^7 K$ and $T > 10^7 K$. We are aware that heavy elements contain more electrons and, thus, collisional excitation process is more likely to happen in comparison to a gas of primordial composition. As a result cooling rate is increased. Additionally, we should mention that these electrons are more strongly bound, which means that in order for collisional excitation to take place more energy is required, which can be translated as higher temperatures. The statements above concern temperatures between $10^4 K < T < 10^7 K$. On the other hand, for temperatures higher than $10^7 K$, as we stressed previously, Bremsstrahlung dominates, which means that the cooling rates are almost equal.

In conclusion, this essay briefly reviewed some of the main aspects of radiative cooling processes in the context of galaxy formation. They provide the necessary physical conditions for collapse and set the mass limits that we observe. A comprehensive study of these processes is therefore key and subject to further studies.

[2]Most of the gas should have cooled and formed stars, and this overpredicts the number density of faint galaxies.

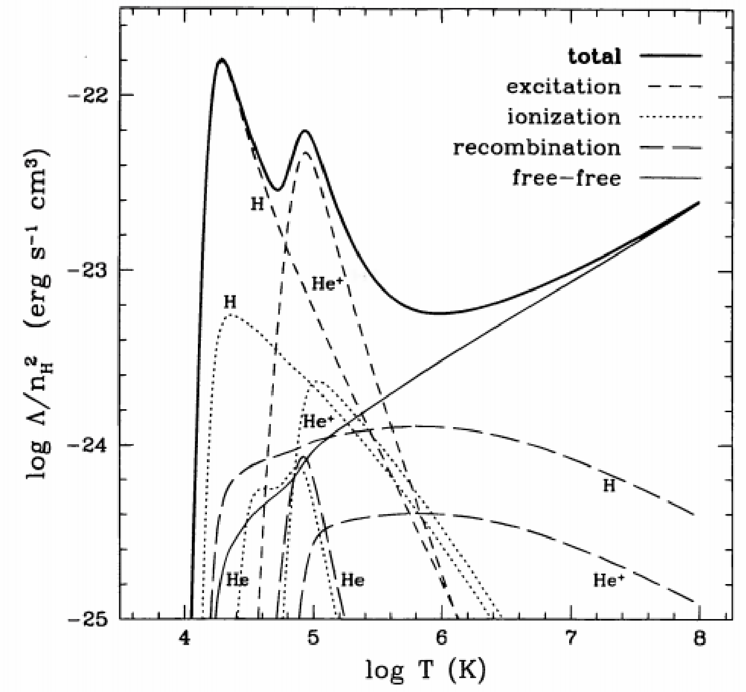

Figure 1: Different cooling rates for a primordial gas that is in collisional equilibrium. Long dashed lines for recombination, dotted lines for collisional ionization, short dashed lines for collisional excitation which dominates at low temperatures and thin solid line for Breemstralhung which dominates at high temperatures. Heavy solid line shows the total cooling rate. Figure taken from [1].

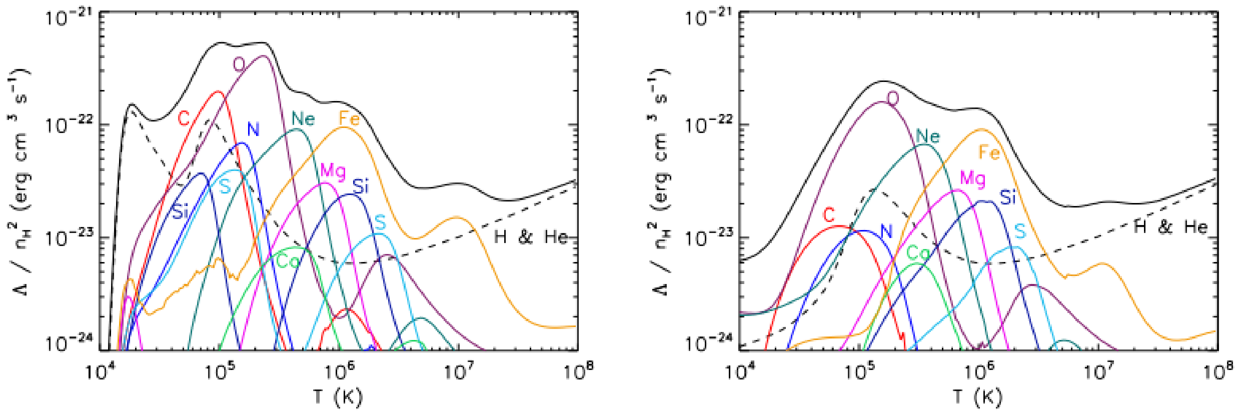

Figure 2: Normalized cooling rates as a function of temperature for solar abundances, assuming either CIE (left-hand panel) or photoionization equilibrium (right-hand panel). The black, solid curve indicates the total cooling rate and the thin, coloured, solid curves show the contributions from individual elements. The black, dashed curve shows the contribution from H and He. Figure taken from [3]

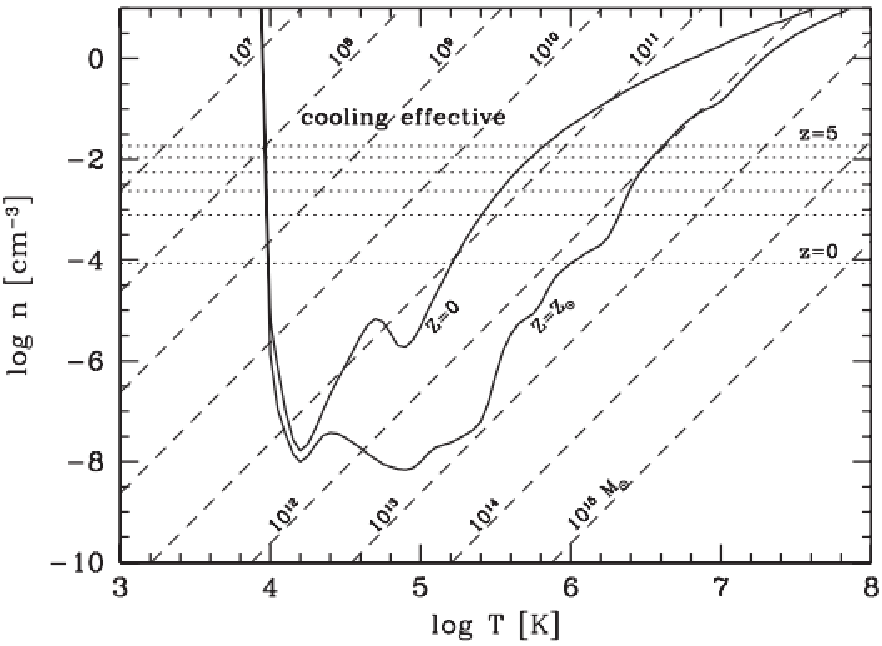

Figure 3: Cooling diagram showing the locus of $t_{\rm cool} = t_{\rm dyn}$ in the n vs T plane. Upper curve corresponds to zero metallicity while lower curve corresponds to solar metallicity. Tilted dashed lines represent lines of constant gas mass. Cooling is only effective for clouds with n and T above the locus which sets the upper limit in galaxy mass. Figure taken from [2].

References

[1] Katz, Weinbrg & Hernquist 1992, ApJS, 105, 19. "*Cosmological simulations with TreeSPH*"

[2] H. Mo, F. van den Bosch and S. White. "*Galaxy Formation and Evolution*", chapter 8.

[3] Wiersma, Schaye and Smith, 2009, MNRAS, 393, 99 "*The effect of photoionization on the cooling rates of enriched, astrophysical plasmas*"

[4] Asaf Pe'er, 2017 "*Basics of Galaxy Formtion*" `http://www.physics.ucc.ie/apeer/PY4111/Structure_formation.pdf`

[5] Jarle Brinchmann, "*The formation of galaxies and large-scale structure*" course, lectures 8,9. `http://home.strw.leidenuniv.nl/~jarle/Teaching/GalaxyFormation/`

[6] C. Fabian, Andrew. (2002), arXiv:astro-ph/0201386 "*Cooling Flows in Clusters and Galaxies*"

[7] Peres C. B., Fabian A. C., Edge A. C., Allen S. W., Johnstone R. M., White D. A., 1998, "*A ROSAT study of the cores of clusters of galaxies – I. Cooling flows in an X-ray flux-limited sample*", MNRAS, 298, 416

[8] Sparke, L.S.; Gallagher, J.S. (2007) (Book). Galaxies in the Universe. Cambridge University Press. ISBN 978-0-521-67186-6

[9] Frank Van Den Bosch, University of Yale, Theory of Galaxy Formation, Lecture 14. `http://www.astro.yale.edu/vdbosch/astro610_lecture14.pdf`