The connection between X–ray Clusters and Star Formation

Paolo Tozzi and Colin Norman

The Johns Hopkins University, 3400 N. Charles, 21218, Baltimore, MD

Abstract. The properties of X-ray clusters of galaxies can be well understood in terms of a competition between shock heating and adiabatic compression. Strong shocks are expected to be important for massive clusters, while adiabatic compression is dominant for small clusters and groups. The scale of the shock/adiabatic transition is marked by a change of slope of the $L-T$ relation and in the global properties of the emitting plasma. This scale is connected to star formation processes. Two quantities are crucial: the average energy injected in the IGM from stars and SNe, and the epoch of the energy injection. We show how these quantities can be synthesized in terms of specific entropy, which ultimately determines the X-ray emission from groups and clusters.

1 The properties of X–ray clusters of galaxies

Clusters of galaxies are objects of great cosmological relevance. In fact, they are believed to constitute a well–defined population of X–ray sources with simple evolutionary behaviour (see, e.g., [2] and references therein). However, their X–ray emission properties are not fully understood: the simple self–similar scaling predicts a relation between the X–ray luminosity and the temperature, $L \propto T^2$ [5], which is at variance with the observed relation $L \propto T^3$. There is further steepening of the $L-T$ at temperatures around 1 keV [7]. Moreover, a sharp transition in the global properties of the emitting plasma is evident below 1 keV [9]. This behaviour has been related to the presence of an entropy minimum in the intergalactic medium (IGM) which, in turn, can be adiabatically compressed in the cluster potential [4][6][1] or accreted through shocks, as suggested by numerical simulations and analytical models [8]. Here we present a simplified argument to show how shock and adiabatic compression compete in a manner regulated by the entropy level of the IGM. The entropy production (before accretion) is due to non–gravitational heating by stars and SNe, and is determined by the average energy and the epoch when such energy is released.

2 The L-T relation in terms of entropy

Here we present a simple argument to understand the $L-T$ relation in terms of entropy production. The minimum entropy of the diffuse IGM is due to non–gravitational energy injection $kT_*$ at the epoch $z_*$, when the gas density was
The specific entropy initially is then $S \propto \log(K_* \rho^{2/3})$. If, in the following, the IGM is only adiabatically compressed, the final relation between density and temperature is $\rho \propto (T/K_*)^{3/2}$. The X-ray emissivity due to bremsstrahlung is $\epsilon_{ff} \propto \rho^2 T^{1/2}$. The central total luminosity of the cluster can be written:

\[ L \propto \epsilon_{ff} V \propto T^{7/2} K_*^{-3} M \propto T^5 K_*^{-3}, \quad (1) \]

where $V$ is the emitting volume. Then, in the limit of pure adiabatic compression, the $L-T$ relation is naturally expected to be steeper than the self similar case (see also [1]).

On the other hand, for a generic IGM distribution we can write $K$ as:

\[ K = T/\rho^{2/3} = (T/T_*) (\rho/\rho_*)^{-2/3} K_* \quad (2) \]

If we neglect further adiabatic compression, the quantity $K$ is determined as follows. In the case in which all the gas is accreted through a strong shock, the ratio $(\rho/\rho_*)$ is simply the maximum compression factor allowed, $(\rho/\rho_*) \rightarrow 4$. If the gas is isothermal, we have $K \propto K_* T$. Substituting the actual value of $K$ for $K_*$ in equation (1), we obtain $L \propto T^2$. Thus, in the limit of strong shocks the self similar scaling is recovered.

Of course it is too simplistic to describe the observed $L-T$ relation in terms of two power–laws. In the real world, the transition between the adiabatic and the shock regime is gradual. However, the scale of the onset of the shocks is an important quantity, and, from observations, is expected to occur around 1 keV. In the following section we show how this scale depends on the entropy, which requires two pieces of information: how much energy is supplied, and when.

### 3 The synergy of X–ray and optical observations

The mass scale at which shocks start to appear, is the scale for which the infalling velocity of the accreting baryons is larger than the sound speed $v_s = (\gamma kT/mHu)^{1/2}$, where $\gamma = 5/3$ and $u = 0.59$ for a primordial IGM.

If the potential well is deep enough, the infall velocity is essentially the free fall velocity $v_{ff}$ (i.e., the baryons follows the dark matter). However part of the work done by the gravitational field goes into compression of the gas. As a result, the baryons are delayed with respect to the dark matter and the infall velocity $v_i$ of the gas is smaller than $v_{ff}$. If we approximate the adiabatic external flow with a Bernoulli equation [10], the condition for the formation of the shock is $v_i > v_s$. This occurs when the gravitational term (or in other words, the free fall velocity) is dominant with respect to the pressure term. At the virial radius, where the gas is accreted and reaches the maximum velocity, this condition can be well approximated by:

\[ \frac{v_{ff}^2}{c_s^2} > \left( \frac{\gamma + 1}{\gamma - 1} \right) - \frac{2}{\gamma - 1} \left( \frac{\rho_0}{\rho_*} \right)^{\gamma - 1} \quad (3) \]
where $\rho_s$ and $\rho_{ta}$ are the densities of the gas at the shock and at the turnaround. Assuming the shock occurs at the virial radius and using mass conservation, we have $\rho_s = f_B \rho_{dm}v_{ff} / v_i$. Expanding in $\rho_{ta}/\rho_s$, at the first order we have $v_{ff} \geq (1.87 - 1.95)c_s$, when $\rho_{ta}/\rho_s \simeq 1/8$ and $1/30$.

If we assume that the entropy minimum $\propto \log(K_*)$ is produced at a single epoch when the IGM was uniform (before the formation of clusters and groups), we have $K_* = kT_* / \mu m_H \rho_s^2/(1+z_*)^2$. Since $c_s^2 = \gamma K_* \rho_s^{2/3}$, the mass scale of the shock/adiabatic transition is determined by $K_*$, as shown in the panel a) of figure 1. The two horizontal lines bracket the mass range roughly corresponding to $0.5 - 2$ keV, with an associated set of values for $K_*$ in the range $0.2 - 1 \times 10^{34}$ ergs $g^{-5/3}$ cm$^2$. Here we use an average $M-T$ relation and take into account the fact that a fraction $\leq 1/2$ of the mass is responsible for more than 80% of the X-ray emission in groups. This argument is analogous to the one presented in [8], based on the entropy core in clusters.

In panel b) and c) we show the behaviour in terms of the two variables $T_*$ and $z_*$ independently. In panel b) we see that the transition scale occurs in the same mass interval for a range of initial temperature $kT_0 = (0.1 - 0.5)$ keV. If the same energy is injected later the entropy and the predicted transition mass scale are higher. This is clear in panel c), where the dependence on $z_*$ for a given energy input is shown. These results hold under the assumption that the gas was uniform at the epoch of entropy production. If, instead, the gas was at a contrast $\delta_*$ with respect to the background density, the relation between energy and epoch is $T_\propto (1+z_*)^2 \delta_*^{2/3}$ for a given $K_*$. This indicates why, after the collapse, a larger energy input is needed to obtain the same effect (i.e., the same $K_*$).

Our discussion shows that the entropy is the key parameter, and demonstrates how both energy and time are equally important in shaping the X-ray emission from large scale structure. Such considerations are mandatory to calculate the energy budget that is necessary to reproduce the observed $L-T$ relation.

### 3.1 What is still missing?

The description of the X-ray properties in terms of entropy can be much more detailed. In particular, the complete density and temperature profiles, including shock heating and adiabatic compression, can be computed in different regimes and cosmological frameworks [10]. However, to define statistically the population of local and high $z$ clusters of galaxies, we still need some important pieces of information.

The injection of $T_*$ is a continuous process, eventually peaking at redshift $z \simeq 2 - 3$. The emitting properties of the ICM will result from the competition between the timescales for dynamical evolution and entropy production. Since there is a large scatter in the formation history of massive halos in
all the hierarchical cosmologies, the properties fluctuate with the epoch of observation and the mass scale. Such intrinsic scatter is one of the most relevant characteristics of the observed $L-T$ relation. The accretion of already virialized, small halos is expected to occur with the free fall velocity, since the bound, clumped gas is not slowed by pressure effect. Consequently, part of the ICM will be always shocked, in an amount depending on the presence of small scale structure. Cooling flows are not included in the present treatment; on the other hand, they are expected to be important, not only for mass deposition in the center, but even for their contribution to the X-ray properties.

In summary, the physics of the X–ray emitting plasma in clusters of galaxies is well understood. The most meaningful parameter is the entropy, which is directly connected to the energy and the temporal scales set by star formation processes. These, in turn, can be directly observed in the optical and infrared bands from ground and space based telescopes. In the near future, the synergy between the X–ray facilities and optical telescopes like the VLT, is expected to give powerful insights in the formation and evolution of cosmic structures.

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