The Virtues of X–ray Clusters and the Entropy of Cosmic Baryons

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Abstract. The thermodynamics of the diffuse, X-ray emitting gas in clusters and groups of galaxies are affected by a certain amount of non–gravitational energy input, as indicated by the scaling properties of X–ray halos. Such a view has been recently confirmed by the detection of an excess entropy in the center of groups. It is not easy, however, to identify unambiguously the source and the epoch of such excess entropy. Here we show that the observations of high $z$ clusters will help in reconstructing both the dynamic and the thermodynamic history of the diffuse cosmic baryons.

1 An unknown factor

The relevance of clusters of galaxies in cosmology cannot be overstated. The cosmological virtue of X–ray clusters mostly resides in the fact that the X–ray properties of the Intra Cluster Medium (ICM) can be used as a direct tracer of the total concentration of mass. The luminosity, and in particular the emission–weighted temperature, offer a unique way to probe the power spectrum of primordial density fluctuations and its evolution.

However, ten years ago it has been realized that a certain amount of non–gravitational energy input is needed to explain the scaling properties of X–ray halos ranging from clusters to groups \[3\]\. Such a non–gravitational contribution does break the simple relation between the distribution of the ICM and that of the total matter. A recent detection \[7\] confirmed the existence of such extra energy, which can be conveniently quantified in terms of an entropy excess with respect to the value expected from gravitational processes only. Furthermore, the specific entropy, defined as $S \propto \ln(K) = \ln(kT/\mu m_p \rho^{2/3})$, determines the properties of both local and distant X–ray clusters. This implies that the X–ray evolution is driven both by the dynamics and the heating history of the gas, which, in turn, may depend on star formation, nuclear activity, etc. In particular, the impact of the non–gravitational processes on the surrounding medium is unknown. Therefore, this unpredictable factor casts a shadow on the virtue of X–ray clusters as tracers of the distribution of matter. From this perspective, a physical model that includes the contribution of a non–gravitational term will restore the reliability of
Figure 1: The evolution of the entropy \((K)\) of three different baryonic shells, including respectively 1%, 10% and 50% of the total baryonic mass at \(z = 0\) as a function of cosmic epoch in a ΛCDM universe. The final mass of the halo is \(10^{15} h^{-1} M_\odot\). The panel on the left has an initial (excess) entropy of \(K_* = 0.1 \times 10^{34} \text{erg cm}^2 \text{gm}^{-5/3}\); the panel on the right \(K_* = 0.3 \times 10^{34} \text{erg cm}^2 \text{gm}^{-5/3}\).

X-ray clusters, and possibly will reveal new virtues.

Here we will show that the entropy is a convenient variable to describe the evolution of the ICM with the inclusion of a heating contribution. As a consequence, looking at the entropy in distant X-ray clusters will give information on the non-gravitational processes that affect the ICM.

2 The Best Record of the History of Baryons

Let us describe the formation of X-ray halos as a spherical, smooth accretion of shells of gas (driven by the dark matter component) with an initial excess entropy \(K_*\), which is the only free parameter. We can clearly distinguish three main phases in the thermodynamic evolution of the diffuse baryons:

- adiabatic compression when the gas starts to be collected in the evolving potential well and its temperature grows as \(kT \propto K_* \rho^{2/3}\);
- shock heating as the infall velocities of the shells become larger than the sound speed; as a consequence, the entropy of the accreted gas shell jumps to higher values;
- further adiabatic compression of the shells enclosed within the shock front; the shells may start to lose entropy due to the radiative cooling, especially in the central regions.
What role is played by the initial excess entropy? In Figure 1 we show the entropy history of three baryonic shells (containing 1%, 10% and 50% of the baryonic mass of a cluster of $10^{15} h^{-1} M_\odot$ total) for two different initial values of $K_*$. In the first case with $K_* = 0.1 \times 10^{34}$ erg cm$^2$ gm$^{-5/3}$, the gas in the center of the halo becomes dense enough to start early cooling. Consequently, the final entropy in the center is much lower than the initial level. In particular, the inner shells can cool completely and drop out from the diffuse, emitting phase. In the case with $K_* = 0.3 \times 10^{34}$ erg cm$^2$ gm$^{-5/3}$, the high initial value of $K_*$ prevents most of the gas from cooling, and a non-negligible entropy level is preserved in the center. These high entropy regions are responsible for the flat cores in the density distribution, that are more extended going from clusters to groups. This mechanism, by setting the appropriate value of $K_*$, bends the $L$–$T$ relation from the self–similar prediction $L \propto T^2$, to the observed average $T^3$. Note also that the entropy level at large radii is unaffected by the initial value, since it is dominated by shock heating.

Summarizing, after a proper treatment of shock heating and cooling, the entropy turns out to be the best record of the thermodynamic history of the diffuse baryons at the scale of groups and clusters. In particular the excess entropy and the cooling processes strongly interfere with each other, in the sense that a non–negligible excess entropy inhibits the radiative cooling. Despite the simplification of assuming a constant and homogeneous value in the external gas, this model can reproduce many scaling properties of X–ray halos if $K_* = (0.4 \pm 0.1) \times 10^{34}$ erg cm$^2$ gm$^{-5/3}$ [8]. Note that the excess entropy can be generated after the collapse, but this would require a much higher energy budget. The last scenario is currently under investigation.

3 The Virtues of Clusters

At this point, it is clear that the evolution of the $L$–$T$ relation is affected to a large extent by the amount of the excess entropy and its time evolution. We recall that both the luminosity and the emission–weighted temperature are affected, even if the $M$–$T$ relation is less dependent on the actual value of $K_*$ [4]. However, once the non–gravitational processes can be included in the excess entropy, the above picture unveils a new virtue of X–ray halos. In fact, the emission properties of clusters and groups reflect both the dynamic and the thermodynamic history of the baryons. Paying the price of a more complex scenario, it will be possible not only to test the cosmology, but also, at the same time, the history of non–gravitational processes like nuclear activity and star formation history (e.g., coupling galaxy formation models with the evolution of X–ray halos, see [9][10][5]).

The simple case of a single value of $K_*$ in the IGM can explain many scaling properties of local clusters, as shown in Figure 2 for the $L$–$T$ and the $K$–$T$ relations (where $K$ is estimated at $r = 0.1 R_{vir}$, see [11]; note also that $L$ at the scale of groups is computed within a radius much larger than the $0.1 h^{-1}$ Mpc used in
Figure 2: The $L-T$ relation (top left panels, data by [6] and [1]) and the $K-T$ relation (top right panels, data by [7]) are shown for a constant $K_* = 0.4 \times 10^{34}$ erg cm$^2$ gm$^{-5/3}$ at $z = 0$ (continuous lines) and $z = 1$ (dashed lines). In the bottom panels, the same is shown for an evolving external entropy $K_* = 0.8 \times 10^{34}(1+z)^{-1}$ erg cm$^2$ gm$^{-5/3}$. Note the different definition for $K \equiv kT/n e^{2/3}$.

[6], see discussion in [8]). In the same Figure 2 we show two different cases for the evolution of the excess entropy. We found that a constant $K_*$ will give a roughly constant $L-T$, while an evolving $K_* \propto (1+z)^{-1}$ will give similar local properties, but a higher $L-T$ (lower $K-T$) at $z \simeq 1$. The observation of distant clusters therefore, will unveil a large part of the history of the cosmic baryons, and can be usefully coupled with observations in other spectral bands in order to unambiguously identify the sources, the time scale and the global energy budget of the non–gravitational preheating.

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