Formation of cold molecular filaments in cooling flow clusters

Yves Revaz$^1$, Françoise Combes$^1$ and Philippe Salome$^2$

$^1$LERMA, Observatoire de Paris, 61 av. de l’Observatoire, 75014 Paris, France. $^2$RIAM, 300 rue de la piscine, 38400 St-Martin d’Hères, France

New CO observations at the center of cooling flow in Perseus cluster (Salome et al. 2006) show a clear correlation of the molecular gas with the previously detected H$_2$ filaments (Combes et al. 2001). In this paper, we present high resolution multi-phase simulations of the Perseus Cluster, taking into account the AGN feedback in form of hot buoyant bubbles. These simulations show that significant amount of gas can cool in cooling flow clusters, in spite of the AGN feedback. The latter provides some heating, but also trigger the hot gas compression, that funnels cooling, even at high radii ($R > 10^7$pc). The time spent by the gas in the intermediate temperature phase ($10^6$K to $10^7$K) is so short, that no gas is expected to be observed below 1KeV in X-rays. The cooled gas flows into the cluster core forming the observed filaments.

Initial Conditions

Our cluster model is designed to fit the Perseus X-ray data of Sanders et al. (2003). The total mass distribution profile follows a pseudo-isothermal spheroid:

$$\rho(r) = \frac{\rho_0}{1 + \left(R/R_c\right)^2}$$

(1)

with $\rho_0 = 1.4 \times 10^{-23} M_{\odot}$pc$^{-3}$ and $R_c = 40$ kpc. The mass distribution is truncated at $R = 220$ pc and the total mass is $5.5 \times 10^{14}$M$_{\odot}$. The gas corresponding to 15% of the total mass has an initial temperature of $10^7$K (white) (the model is rotated from 10 degrees around the $x$ axis). They are generated by symmetric pairs, in average each 200 Myr. Bubbles parameters are randomly chosen with

$$\frac{\alpha}{\alpha} = \frac{\beta}{\beta} \times \frac{\gamma}{\gamma}$$

(2)

where $\alpha$ and $\beta$ correspond to the unperturbed intra-cluster gas density and specific energy at the same radius.

Global evolution

Evolution of an isolated bubble

The evolution of an isolated bubble is generated at $t = 0$ (Fig. 1) by injecting energy in hot intra-cluster gas bubbles which are then driven buoyantly at higher radius. Bubbles are defined by their position $R$, diameter $D$, temperature $T_b$, over pressure $\beta$, and angle $\alpha$ (angle of the bubble with respect to the $y$ axis). They are generated by symmetric pairs, in average each 200 Myr. Bubbles parameters are randomly chosen in the ranges given by Tab. 1 and are actually not correlated to the cluster accretion rate.

$$\text{Radius } R = 50 - 500 \text{ kpc}$$
$$\text{Diameter } D = 20 - 40 \text{ kpc}$$
$$\text{Over pressure } \beta = 1 - 2$$
$$\text{Temperature } T_b = 5 \times 10^6 - 2 \times 10^7 \text{ K}$$
$$\text{Angle } \alpha = 0$$

Table 1. Initial parameters for the bubbles.

Fig. 2. Evolution of the cluster temperature during 4 Gyr, from $10^7$K (black) to $2 \times 10^5$K (red). The box dimension is 400 x 400 kpc.

Evolution of a isolated bubble

Fig. 1. Evolution of an isolated bubble. Top panels: Temperature from $10^7$K (black) to $2 \times 10^6$K (red). Bottom panels: Radial velocities from $10^5$km/s (black) to $10^4$km/s (red). The model is rotated from 10 degrees around the $x$ axis. The box dimension is 200 x 200 kpc.

Cold gas formation

In addition to slowing down the cooling flow at the center of the cluster, our simulation also show how AGN feedback may trigger cold gas formation at high radius ($R > 10^7$pc). Physical conditions for efficiently cool intra-cluster gas occur either when the gas is less than $10^5$K or when its density is sufficiently high. Buoyant bubbles are responsible of strong inhomogeneities in temperature (see Fig. 2) as well as in density of the intra-cluster medium. In Fig. 3, we show here cooling falling gas (trunk of a bubble, see Fig. 1) is trapped between an old and a new rising bubble and is compressed to a state where its cooling time is sufficiently short to let the gas becomes cool in a fraction of Gyr. In Fig. 4, the cluster is seen 300 Myr later. The short cooling time gas of Fig. 2 has now cooled down below $10^5$K. As it is not supported by the hot gas pressure, it falls radially to the center, forming a filament like structure ($R = 50$ to $R = 10^4$pc) of mass $1.5 \times 10^{14}$M$_{\odot}$. In the filament, the gas density is not high enough to form stars.

Fig. 3. Gas temperature at $t = 270$ Myr. The white contour (pointed by black arrow) indicate the position of the gas having a short cooling time $\tau_c < 1.3$ Gyr that will be transformed into cold gas in Fig. 4. The upper left box corresponds to the region zoomed in Fig. 4. The box dimension is 400 x 400 kpc.

Fig. 4. Gas temperature between $t = 2500$ Myr and $t = 3100$ Myr, from $10^7$K (black) to $2 \times 10^5$K (red). The small black dots pointed by the black arrow represents cold gas ($T < 10^5$K falling into the cluster center. The box dimension of each panel is 200 x 200 kpc.

The lack of emission below 1KeV

In order to illustrate the very efficient cooling of the gas in over-density regions, Fig. 5 (left) shows the temperature-evolution of the gas within the filament of Fig. 4. At $t = 2700$, the gas has a temperature of about $7 \times 10^6$K. When the temperature of $3 \times 10^5$K is reached, the cooling is highly enhanced, causing the gas temperatures to quickly fall below $10^5$K. The very short cooling time below $7 \times 10^5$K may also explain the paucity of flux detected below 1keV in cooling flow cluster. The right part of Fig. 5, show an histogram of the mass fraction of gas as a function of its temperature for the whole cluster. It clearly appears that due to its very short cooling time, the gas is very quickly transported from $10^5$K to $10^6$K, inducing a gap between these two values.

References


Fig. 5. (a) Temperature evolution of particles within the filament of Fig. 4. (b) Histogram of the mass fraction of gas as a function of its temperature. In blue, at $T = 2$ in red, after 1Gyr.