ENTROPY LIMIT AND THE COLD FEEDBACK MECHANISM IN COOLING FLOW CLUSTERS

Noam Soker

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ABSTRACT

I propose an explanation for the finding that star formation and visible filaments strong in Hα emission in cooling flow clusters occur only if the minimum specific entropy and the radiative cooling time of the intracluster medium (ICM) are below a specific threshold. The explanation is based on the cold feedback mechanism. In this mechanism, the mass accreted by the central black hole originates in nonlinear overdense blobs of gas residing in an extended region of the cooling flow region. I use the criterion that the feedback cycle period must be longer than the radiative cooling time of dense blobs, for large quantities of gas to cool to low temperatures. The falling time of the dense blobs is parameterized by the ratio of the infall velocity to the sound speed. Another parameter is the ratio of the blobs’ density to that of the surrounding ICM. By taking the values of the parameters as in previous papers on the cold feedback model, I derive an expression that gives the right value of the entropy threshold. Future studies will have to examine in more detail the role these parameters play, and will have to show that the observed sharp change in the behavior of clusters across the entropy, or radiative cooling time, threshold can be reproduced by the model.

Subject headings: cooling flows — galaxies: active — galaxies: clusters: general — intergalactic medium — X-rays: galaxies: clusters

1. INTRODUCTION

In the last decade, it has become clear that the intracluster medium (ICM) in cooling flow (CF) clusters of galaxies and CF galaxies must be heated, and that the heating process should be stabilized by a feedback mechanism (see review by McNamara & Nulsen 2007). However, in many cases, the heating cannot completely offset the cooling (e.g., Wise et al. 2004; McNamara et al. 2004; Clarke et al. 2004; Hicks & Mushotzky 2005; Bregman et al. 2006; Salome et al. 2008), and some gas cools to low temperatures and flows inward (e.g., Peterson & Fabian 2006). The mass inflow rate is much below the one that would occur without heating, and the flow is termed a moderate cooling flow (Soker et al. 2001; Soker & David 2003; Soker 2004).

One of the likely ingredients of the moderate CF model is a cold feedback process (Pizzolato & Soker 2005; Soker 2006; Pizzolato 2007). In the cold-feedback model, the mass accreted by the central black hole originates in nonlinear overdense blobs of gas residing in an extended region of $r \sim 5$–$30$ kpc; these blobs are originally hot, but then they cool faster than their environment and sink toward the center. The mass accretion rate by the central black hole is determined by the cooling time of the ICM, the entropy profile, and the presence of inhomogeneities (Soker 2006). Most important, the ICM entropy profile must be shallow for the blobs to reach the center as cold blobs. This accretion process is different from the commonly assumed accretion mode in feedback models in which the black hole accretes hot gas (the hot feedback mechanism) from its vicinity, e.g., via a Bondi-type accretion flow (e.g., Churazov et al. 2002; Nulsen 2004; Omma & Binney 2004; Chandran 2005; Croton et al. 2006; Balmaverde et al. 2008).

Among other things, the cooling of the ICM to low temperatures is inferred from star formation (e.g., Rafferty et al. 2008) and from cool filaments via their Hα emission (Hα filaments). Recently, Cavagnolo et al. (2008) found that almost all clusters with strong Hα emission have a central entropy of $K \equiv k T n_e^{-2/3} \lesssim 30 \text{ keV cm}^2$; here $k$ is the Boltzmann constant, $T$ is the ICM temperature, and $n_e$ its electron density. This relation might be better presented as a relation between star formation (SF) and the radiative cooling time: no star formation is seen if the radiative cooling time is $t_{rad} \approx 5 \times 10^8$ yr or if the entropy is $K \gtrsim 30 \text{ keV cm}^2$ (Rafferty et al. 2008).

Voit et al. (2008) suggest that this $K$-$Hα$ (or SF-$t_{rad}$) relation results from two competing factors: (1) the radiative cooling of cooler regions and (2) the heat conduction into these cooler regions. In a high-entropy ICM, the heat conduction manages to prevent thermal instabilities that could potentially form Hα filaments. For the cooling function dependence on temperature, Voit et al. (2008) assumed $\Lambda \propto T^{7/2}$ (or $Hα$-X-ray). However, for most clusters, the temperature in the inner region is $T < 3$ keV, and, for a composition above half a solar, the cooling function is basically constant in the range $\sim 1.7$–$3$ keV. This introduces a very small change in the numerical value that is not significant, but it does show that the dependence on some power of the entropy is an approximate one. The same holds for the explanation proposed here (see § 3). More significant is their assumption that the size of the cooling region is of the order of the radius of the cluster at the location of the region. The instabilities at such a scale are likely to be very fragmented (fractal), such that the heat conduction is more efficient than what Voit et al. (2008) assume (because the temperature gradient is larger across the smaller dimension of a filament and because the surface area for heat conduction is much larger). Also, if in some regions the magnetic field lines are closed on a much smaller scale than the distance to the cluster center $r$, then the heat conduction is limited to within magnetic flux tubes (Soker et al. 2004; Soker 2004). Another point of concern is discussed in § 3.

A detailed study of the two competing factors—radiative cooling of cool filaments, at a temperature of $\sim 10^4$ K, and heat conduction from the ICM—is presented in Nipoti & Binney (2004). They find that cool filaments survive only if the ICM density is high and the ICM temperature is low (i.e., has a low entropy). However, Nipoti & Binney (2004) argue that the filaments do not originate from the hot ICM, as Voit et al. (2008) consider, but rather the cool gas originates from other

1 Department of Physics, Technion–Israel Institute of Technology, Haifa 32000, Israel; soker@physics.technion.ac.il.
sources, e.g., from active galactic nucleus (AGN) activity and external infall.

Voit et al. (2008) note that the radiative cooling rate of the ICM depends on entropy and that the K-Hα relation might be alternatively related to the short radiative cooling time of the low-entropy ICM and, hence, better termed the SF-τcool relation (Rafferty et al. 2008). In this Letter, I use the radiative cooling time and the infall time of dense blobs as competing factors, as developed for the cold feedback mechanism by Pizzolato & Soker (2005), to explain the K-Hα (SF-τcool) relation.

2. THE COLD FEEDBACK EXPLANATION

In the cold feedback mechanism, cold dense blobs fall toward the center of the cluster and “feed” the central AGN. If a region in the cluster is perturbed and blobs start to cool, then, as the first blobs fall and reach the center, an AGN outburst will heat the perturbed region and prevent further cooling. The condition for large quantities of gas to cool is for the feedback cycle to be longer than the radiative cooling time

\[ t_{\text{cycle}} \approx t_{\text{cool}}. \]

The cooling time of a blob with a density of δ times the ambient density, hence a temperature δ times lower, is given by

\[ t_{\text{cool}} = \frac{nk(T/\delta)}{\delta n_e n_p \Lambda}. \]  

where \( n, n_e, \) and \( n_p \) are the total, electron, and proton densities of the ICM, respectively, and \( T \) is the ICM temperature. In equation (2), the increase in the cooling function \( \Lambda \) and the increase in the density, with decreasing temperature of the cooling blob, were accounted for. For the relevant temperature range here, 1.5 keV \( \approx kT \approx 4 \) keV, and for solar composition, the cooling function is \( \Lambda \approx 2 \times 10^{-23} \text{ ergs cm}^2 \text{ s}^{-1} \) (Gaetz et al. 1988).

For the feedback cycle time, I assume the following. The dense blob falls with its terminal velocity \( v_t \). Pizzolato & Soker (2005) studied the fall of dense blobs through the ICM and found the terminal velocity to be

\[ v_t \approx 60 \left( \frac{a}{100 \text{ pc}} \right)^{1/2} \left( \frac{g}{10^8 \text{ cm s}^{-2}} \right)^{1/2} \left( \frac{\delta}{3} \right)^{1/2} \text{ km s}^{-1}, \]  

where \( a \) is the radius of a spherical falling blob and \( g \) is the cluster’s gravitational field. In this Letter, I scale the blob size and density contrast with the typical values used by Pizzolato & Soker (2005). I incorporate the radius of the blob and δ into a parameter \( \eta \), such that the average inflow velocity of the blob is \( \eta C_s = \eta (5kT/3\mu m_H)^{1/2} \), where \( C_s \) is the sound speed of the ICM. For a cluster temperature of 2 keV, a velocity of 50 km s\(^{-1}\) corresponds to \( \eta = 0.07 \). The feedback cycle period is then

\[ t_{\text{cycle}} = \frac{r}{\eta C_s}. \]

Inserting equations (2)–(4) into equation (1) gives the condition for the formation of large quantities of cold gas:

\[ r \approx D_c = \eta C_s \frac{n_k T}{\delta^2 n_e n_p \Lambda} = 1.1 \left( \frac{\eta}{0.1} \right) \left( \frac{\delta}{3} \right)^{-2} \times \left( \frac{2 \times 10^{-23} \text{ ergs cm}^2 \text{ s}^{-1}}{\Lambda} \right)^{-1} \times \left( \frac{K}{10 \text{ keV cm}^2} \right)^{3/2} \text{ kpc}, \]  

where \( K = kT n_e^{-2/3} \) is the entropy. The above condition implies that, for blobs to cool within the cooling radius, the entropy must be lower than some threshold.

The power of the entropy in equation (5) is an approximate one. The value of 3/2 was obtained under the assumption that the inflow speed of dense blobs is proportional to the sound speed, and under the assumption that the cooling gas is in the temperature range where the cooling function does not depend on temperature. The last assumption is a good approximation for most clusters near the threshold \( K \approx 30 \) keV cm\(^2\). In any case, in the cold feedback mechanism, what matters is the radiative cooling time. This is also seems to be the case from observations (Rafferty et al. 2008).

Equation (5) is sensitive to the values of δ and \( \eta \). Here I simply took the same values used by Pizzolato & Soker (2005). In obtaining \( \eta \), I assumed a blob size of \( \sim 100 \) pc, as the scaling used by them, and for δ I took the value of an unstable blob used by them. The parameter \( \eta \) is dependent on the blob radius \( a^{1/2} \) and on the density contrast \( \delta^{3/2} \). Therefore, equation (5) practically depends on \( a^{1/2} \) and \( \delta^{3/2} \). The limit value of 1.1 kpc in equation (5) is similar to the one obtained by Voit et al. (2008). With their typical value of the heat conduction suppression factor \( f_c = 0.2 \), their equation (2) has a limit of 1.8 kpc. However, they use a lower value for the cooling function (because they take the dependence to be \( \Lambda \propto T^{1/2} \)). If I take the same value for \( \Lambda \) as they took, then the two coefficient are almost equal. Still, the sensitivity of equation (5) to the parameters \( \eta \) and δ is a somewhat weak point of the proposed explanation.

The cold feedback mechanism can also account for the finding that the low-entropy clusters have stronger radio emission (Donahue et al. 2005; Cavagnolo et al. 2008). The same source of blobs that leads to the formation of Hα filaments will feed the AGN activity. Cavagnolo et al. (2008) noticed that, below the threshold \( K < 30 \) keV cm\(^2\), there is no correlation between radio power and the central entropy. They tentatively speculated that this lack of correlation implies that cold-mode accretion (Pizzolato & Soker 2005; Hardcastle et al. 2007) might be the dominant process feeding the AGN.

3. DISCUSSION AND SUMMARY

In this Letter, I show that the finding of Rafferty et al. (2008) that no star formation (SF) is seen if the radiative cooling time is \( \tau_{\text{cool}} \approx 5 \times 10^7 \) yr and that the finding of Cavagnolo et al. (2008) that almost all clusters with strong Hα emission have a central entropy of \( K \approx kT n_e^{-2/3} \approx 30 \) keV cm\(^2\) might be explained by comparing the cooling time of dense blobs in the ICM (eq. [2]) with the response time (cycle time) of the AGN feedback heating. This time is taken to be equal to the fall time of the dense blobs toward the center (eq. [4]). Many dense blobs will cool to low temperatures if the response time is longer than their cooling time.
This leads to equation (5), which is the main result of this Letter. It shows that, for blobs to cool within the CF radius, the entropy must be lower than some threshold.

The feedback heating of the ICM in this model is maintained by dense blobs that are accreted by the central black hole and originate in nonlinear overdense blobs of gas residing in an extended region of $r \sim 5$–30 kpc; this is the cold feedback mechanism (Pizzolato & Soker 2005; Soker 2006).

Equation (5) can be compared with the one derived by Voit et al. (2008): $r \approx (4/100 \, \mathrm{keV} \, \mathrm{cm}^{-2})^{1/2} (\tau)^{1/4}$, where $f_c$ is the suppression factor of the heat conductivity, which is taken to be $f_c \sim 0.1$–1 in their model. The similarity of the expressions are interesting. They have the same dependence on the entropy, a similar numerical factor, and some parameters. Voit et al. (2008) consider their expression to satisfactorily explain their observations. The similarities between the two conditions show that the cold feedback explanation proposed here should be considered in future studies as well. In particular, the result is satisfactory if we consider the crude derivation performed here, and the inhomogeneous nature of the ICM, where large regions with lower-than-average entropy exist. The dense blobs will be more likely to develop in these regions.

The value of $f_c \sim 0.1$–1 and the large thermally unstable regions considered by Voit et al. (2008) imply that heat conduction is globally important in the CF region. However, models based only on global heat conduction are unstable and require fine-tuning (Bregman & David 1988; Soker 2003; Kim & Narayan 2003). The explanation of Voit et al. (2008) requires a stabilizing mechanism. Recently, Guo et al. (2008) built a feedback model based on both heat conduction and AGN heating. They showed that the AGN heating stabilizes the feedback mechanism.

There is a price to be paid for achieving the stability found in the model of Guo et al. (2008). (1) The inner boundary of their simulation is at $r = 1$ kpc. They require that all the mass that enters the $r = 1$ kpc sphere must reach the central black hole, and that the mechanical energy of the launched jet must be $L_{\text{jet}} = 4M(1$ kpc)$^{-1}c^2$, with $c = 0.1$–0.3. This is an extremely efficient conversion of the mass inflowing at $r = 1$ kpc to the mechanical energy of the jets. (2) In their stable model of A1795 (their model A3), the entropy decreases with radius, such that the model is unstable to convection. This might not be a big concern, as by using a different AGN heating prescription, the negative entropy might be removed (F. Guo 2008, private communication). (3) In their best models of A2199 (model B3) and A2052 (model C3), the response time of the AGN is too long.

Using their values of the mass inflow rate and density at $r = 1$ kpc, the inflow velocity $v/(1$ kpc) can be calculated. The response of the accreting black hole to changes in the ICM is on a timescale of $\tau = 1$ kpc/$c^2$. I find $\tau = 7$ Gyr for model B3 and $\tau = 8$ Gyr for model C3. In both cases, the response time $\tau$ is about an order of magnitude longer than the cooling time in the center of these clusters (0.6 and 1.1 Gyr, respectively). This shows that the AGN heating has no time to respond to changes in the thermal state of the ICM. It is possible that this problem will disappear if an episodic AGN heating is applied (F. Guo 2008, private communication).

The explanation proposed here for the K-Hα relation (or SF-τrelation) has to overcome some difficulties as well. In the first step, it will be required to show that reasonable values for the two parameters used in the model ($\delta$ and $\eta$) can lead to the sharp transition from bright Hα clusters, for $K < 30\, \mathrm{keV}\, \mathrm{cm}^{-2}$, to clusters with no, or very weak, detection of Hα emission. Here I note that the values of $\eta$ and $\delta$ used here are the typical values used by Pizzolato & Soker (2005). If I insert the threshold value of $K = 30\, \mathrm{keV}\, \mathrm{cm}^{-2}$ found by Cavagnolo et al. (2008) and $\delta = 2.5$–3 used by Pizzolato & Soker (2005) into equation (5), I find that the numerical value is $\sim 13$–6 kpc. This is inside the range of $r \sim 5$–30 kpc considered by Pizzolato & Soker (2005) to be the region where dense blobs originate. In a later step, numerical simulations of dense blobs in the ICM should show that the formation of cold clouds, which are the source of Hα emission, depends on entropy in the way usually observed.

The main difference between the explanation proposed here and that of Voit et al. (2008) is the importance of the global heat conduction. In recent years, the debate on whether or not global heat conduction in CF clusters is important has intensified. If it turns out that global heat conduction is important, then the explanation proposed here must be ruled out. If it turns out that global heat conduction is not important, then the explanation by Voit et al. (2008) must be ruled out. In the cold feedback mechanism, cold blobs feed the central black hole. Therefore, in CF clusters with strong AGN activity, some cold blobs exist close to the center. Therefore, the prediction here is that a very low level of Hα emission might be detected, even in CF clusters with high entropy.

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