HEATING OF THE ICM DUE FOSSIL PLASMA

M. Hoeft, M. Brüggen
International University Bremen
Campus Ring, 28759 Bremen, Germany
M.HOEFT@IU-BREMEN.DE

Abstract

Huge amounts of highly relativistic plasma are emitted into the intracluster medium (ICM) by active galactic nuclei (AGN). This plasma rises buoyantly to the fringes of the cluster. However, disruption due to hydrodynamical instabilities slows down the motion of the plasma. Simultaneously radiative losses cool down the plasma. In the very end the plasma is mixed into the ICM. We investigate the effect of heating the ICM using the effervescent heating model. We apply this to a spherically symmetric cluster model with a cold core in the center and assume a single-fluid ICM. We found that even a small effervescent heat reduces the accretion onto the core. Moreover, the mass deposition rate may be by orders of magnitude smaller than inferred from usual cooling-flow formula.

1 Introduction

Clusters of galaxies are formed by smooth accretion of gas, frequent merging of smaller groups to a cluster and less frequent mergers of clusters of similar size. All these processes heat the ICM by generating weak or strong shocks, which heat the ICM to its temperature of 1-10 keV. However, numerical simulations overestimate the amount of baryons which are bound in galaxies (Balogh et al., 2001). To reduce the condensed baryon fraction additional heating has to be introduced. Cooling-flow clusters show a temperature decrease toward the center, which result in a cooling times much shorter than the Hubble time (e.g., Abell 1835, Schmidt et al. (2001)). Since only little emission is found from gas with temperature lower than $T_{\rm vir}$/3 radiative losses have to be replenished by some mechanism, see Donahue & Voit (2004) and references therein. Several models have been proposed assuming that the AGN provide the necessary heat. However, the mechanism how the originally mechanical work is transferred into the ICM is still not fully identified. Ruszkowski et al. (2004), e.g., found that 40 percent of the into bubbles injected energy may be dissipated by viscous effects.

2 Effervescent heating

AGN inject a large amount of magnetized, relativistic plasma into the ICM. This radio plasma emits mainly synchrotron radiation. However, after a typical time of 10^8 years the plasma has cooled radiatively such that the remaining radio emission is difficult to detect. The remnants of radio lobes are called 'radio ghosts' or 'fossil radio plasma'. Substantial evidence for radio ghosts has come from the detection of cavities in X-ray surface brightness maps of clusters of galaxies.

Bubbles rise buoyantly to the periphery of the cluster. Since the pressure P in the ICM decreases with radius the bubbles expand as they rise out of the cluster. The volume heating function due to pdV-work is given by

$$h(r) \propto P^{(\gamma_b-1)/\gamma_b} \frac{1}{r} \frac{\mathrm{d}\ln P}{\mathrm{d}\ln r}, \quad (1)$$

where γ_b denotes the adiabatic index inside the bubbles (Ruszkowski & Begelman , 2002). Assuming that all this work is transferred into heat and time between two AGN outbursts is short compared to the cooling time in the ICM an average heating function can be introduced. Moreover, bubbles are likely disrupted by Rayleigh-Taylor instabilities. An estimate for the lifetime of a bubble may be provided by the growth time $\tau_{\rm RT}(d)$ of the largest mode possible (Soker et al., 2002)

$$\tau_{\rm RT}(d) = 14\mathrm{Myr}\sqrt{\frac{\mathrm{d}/10\mathrm{kpc}}{\mathrm{g}/10^7\mathrm{cms}^{-2}}}, \quad (2)$$

where d denotes the size of the bubble. Since the rise velocity $v_{\rm buoy}$ and the life-time scale with the size of the bubbles, the fragments obtained after splitting a

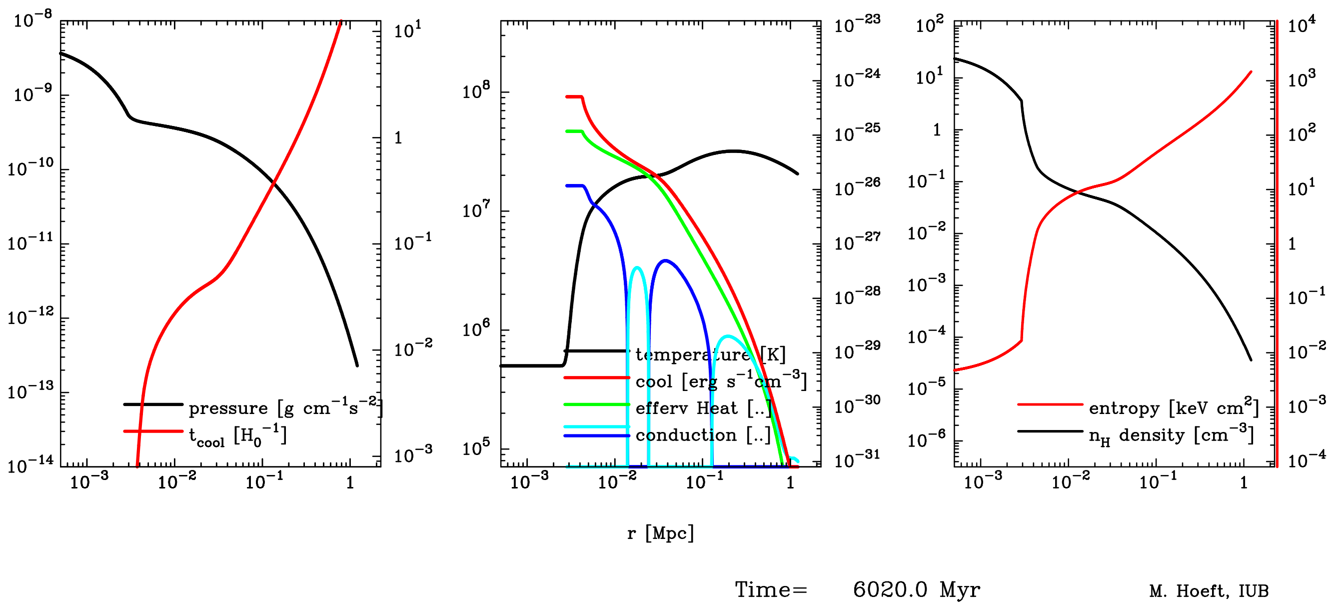

Figure 1: Radial profiles after $\sim$ 6 Gyr evolution. Black lines in the left, center and right panels show the pressure, temperature and hydrogen number density as a function of radius. On the left in red the cooling time in units of the Hubble time is shown. In the center panel you see the radiative cooling (red) and heating profiles: green shows the effervescent heating. Blue shows the heating and cyan the cooling caused by thermal conduction. After about 3.6 Gyr the central region collapses and forms the cold core. Note, we set a minimum temperature of 5×10^5 K.

bubble virtually stop in th ICM. Estimating the radius at which this occur we found that most fragments will be deposited at a distance $r_{\rm disr}$ of a few hundred kpc from the center. As a result the effervescent heating rate will be reduced in the periphery of the cluster. Thus, the volume heating rate is effectively cut-off. We approximate this by the factor

$$\frac{1}{(r + r_{\rm injec})^2} \exp\{-(r/r_{\rm disr})\}, \qquad (3)$$

where $r_{\rm injec}$ denotes the radius at which the bubbles are injected.

3 Self-regulating feedback

In spherically symmetric model we study how the AGN feedback may help to suppress the cooling catastrophe of a cluster. We start from an almost constant temperature profile an consider first only the radiative cooling. The radial profiles are evolved by calculating at each time the change of entropy and by determining the new profiles assuming that the pressure at r_{200} is constant (Roychowdhury et al., 2004). After the central cooling time a cold core forms for which we set a minimum temperature. Now we relate the volume heating function to mass accretion onto the core. We assume that the total luminosity $\mathcal{L}_{\rm eff}$ is proportional to the mass accretion onto the core with an efficiency ϵ. See details in a forthcoming paper Hoeft & Brüggen (2004). This results in a self-regulating system. If the efficiency is sufficiently high, the heating reduces or even switch off the accretion.

We also take into account the effect of heat conduction. We assume that the conductivity is in the range 0.1 - 0.3 times the Spitzer conductivity.

Figure 1 shows various profiles after some time of feedback. A cluster with virial mass of 6×10^{14} $M_\odot$ is modeled. The dark matter distribution is assumed to obey a NFW-profile with concentration 4.0. The radial distribution of effervescent heating comes close to the radiative losses and almost replenishes them. In this way a cluster reaches a quasi-stationary state, i.e., the accretion is small and radiative losses are balanced, see Fig. 2. However, even a lower efficiency and in result a lower effervescent heating also stabilizes the cluster over several Gyr. Thus, a wide range of efficiencies ϵ would result in a quasi-stable solution. In effect this regulates rather the accretion onto the core, than the effervescent luminosity.

4 Accretion versus cooling flow

From X-ray observations the mass deposition rate is typically inferred by

$$\dot{\mathrm{M}}_{\mathrm{cool-flow}} \approx \frac{2}{5} \frac{\mu m_{\mathrm{H}}}{k_B T_X} L_X(< r_c), \qquad (4)$$

where r_c is the cooling radius at which the cooling time equals the Hubble time. The value obtained from Eq. (4) exceeds always by far the accretion rate determined by our model. The accretion is in the range of 1 to 100 $M_\odot$ yr^{-1}, depending on the efficiency. In the case of the higher values the heating is almost without effect. On the other hand the derived value for the cooling-flow $\dot{\mathrm{M}}_{\mathrm{cool-flow}}$ is only slightly altered by the heating, since predominantly regions about 100 kpc contribute to $\dot{\mathrm{M}}_{\mathrm{cool-flow}}$. This shows that, if the cooling of the cluster proceeds with a single-fluid, the radiative losses of the entire volume has to be at least partially replenished to avoid a global cooling of the cluster. But only in the central, i.e., less than 10 kpc, region gas may drop below temperatures about 10^7 K. Feedback in this central regions regulates the accretion onto the core.

It is also worth to note, that this self-regulating heating mechanism keeps the temperature profile decreasing toward the center, in accordance with the observations. Raising the temperature in central regions significantly would immediately switch off the accretion and consequently also the heating.

5 Conclusion

The huge radio lobes inflated by AGN cool by synchrotron radiation and form cocoons of fossil radio plasma. This bubbles rise buoyantly through the ICM. Assuming that the mechanical work released when the bubbles rise is transferred locally into heat, motivates the effervescent heating model. We apply the resulting heating function to a spherically symmetric cluster model. We assume that a cold core forms in the center of the cluster and cooling results in an increase of this core. This corresponds to a single-phase ICM, and no cold gas is formed further away from the core. We assume that the effervescent luminosity is proportional to the mass accretion onto the core.

This results in a self-regulation system: changing the efficiency, i.e., how much heat is released per accreted mass, mainly alters the accretion rate onto the core. The rate increases until locally, i.e., around the core, the gas is heated sufficiently to suppress the accretion.

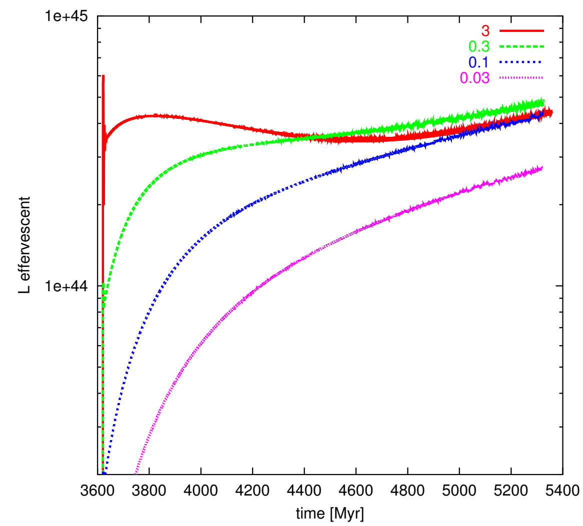

Figure 2: The effervescent luminosity as a function of time. We vary the efficiency from 0.03 to 3×10^{45} erg s^{-1} / 30 $M_\odot$ yr^{-1}. The curves indicate that if a luminosity of $\mathcal{L}_{\mathrm{eff}} \approx 4\times10^{45}$ erg s^{-1} is reached the accretion is strongly suppressed.

Thus, with time heating and radiative cooling come almost in balance over the entire cluster.

The accretion rate is much smaller than the mass deposition rate inferred from Eq. (4). This is also true for if the feedback is very inefficient. Thus in a single-medium ICM the cooling flow always over-estimates the accretion onto a cold core.

References

Balogh, M. L., Pearce, F. R., Bower, R. G., Kay, S. T. 2001, MNRAS, 326, 1228

Donahue, M., Voit, G. M. 2004, in *Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution*, eds. Mulchaey, J. S., Dressler, A., Oemler, A.

Hoeft, M., Brüggen, M. 2004, in preparation

Roychoudhury, S., Rushkowski, M., Nath, B. B., Begelman, M. C. 2004, ApJ, submitted, astro-ph 0401161

Ruszkowski, M., Begelman, M. C. 2002, ApJ, 581, 223

Ruszkowski, M., Brüggen, M., Begelman, M. C. 2004, ApJ, submitted, astro-ph 0403690

Schmidt, R. W., Allen, S. W., Fabian, A. C. 2001, MNRAS, 327, 1057

Soker, N., Blanton, E. L., Sarazin, C. L. 2002, ApJ, 573, 533