Gravitational heating, clumps, overheating

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Abstract. There is no shortage of energy around to solve the overcooling problem of cooling flow clusters. AGNs, as well as gravitational energy are both energetic enough to balance the cooling of cores of clusters. The challenge is to couple this energy to the baryons efficiently enough, and to distribute the energy in a manner that will not contradict observational constraints of metallicity and entropy profiles. Here we propose that if a small fraction of the baryons that are accreted to the cluster halo are in the form of cold clumps, they would interact with the hot gas component via hydrodynamic drag. We show that such clumps carry enough energy, penetrate to the center, and heat the core significantly. We then study the dynamic response of the cluster to this kind of heating using a 1D hydrodynamic simulation with sub-grid clump heating, and produce reasonable entropy profile in a dynamic self-consistent way.

1. Introduction

Galaxy clusters grow by accreting dark matter and baryons from their surroundings. This is partly a continuous process of relatively smooth accretion, and partly via mergers. The existence of a visible, extended X-ray halo as well as limits on the size of the CD galaxy are two indicators that the smooth, continuous accretion is the more pronounced of the two. The baryons that are accreted in this process settle in hydrostatic equilibrium within the cluster’s potential well. During this process they achieve virial equilibrium by passing through the virial shock and converting the kinetic energy of the infall to thermal energy. The baryons, at a temperature of a few keVs, cool primary by emitting Bremsstrahlung radiation which easily escape the halo and is observed by X-ray telescopes. After de-projection (tomography) of the luminosity and spectrum, radial profiles of temperature and densities are derived, and one can deduce the cooling times of the gas, which, for the centers of cooling flow cluster, is \( \leq 1\text{Gyr} \), much shorter than the age of typical clusters that, according to \( \Lambda CDM \) formation history (Press & Schechter 1974) should have been in place at \( z \geq 1 \). Had this gas cooled, i) cool gas would have been seen in the halo (no gas below \( T = \frac{4}{7}T_{\text{vir}} \) is observed), ii) a census of all the baryons in galaxies is significantly smaller than amount of gas that was expected to cool from the halo, and iii) the star formation within the CD would have been \( 10^2 - 10^3 M_\odot/\text{yr} \) (two orders of magnitude larger than typically observed). These three contradictions are three manifestations of the overcooling problem of cooling flow clusters. It is highly unlikely that there is a “hidden” baryonic component in cluster halos, so most
explanations invoke some kind of heating mechanisms that would balance the cooling, keeping the gas hot and diffuse.

The energies needed to compensate for the rapid cooling of cluster halos are \( \sim 10^{45}\text{erg/sec} \) which, over the lifetime of the cluster amounts to \( \sim 10^{62}\text{erg} \). These required energy rates can originate from AGN emission from the CD (Ciotti & Ostriker 1997, as well as many others), and by gravitational energy. Diffuse baryons falling into a gravitational well convert gravitational energy to kinetic, and ultimately to thermal. This thermal input into the system is usually local, and acts to heat the infalling gas itself. It is necessary to couple this freshly accreted, hot gas, with the central cooling gas. Narayan & Medvedev (2001) have studied conduction and turbulence that could potentially couple the external part to the inner halo. Kim & Narayan (2003), as well as others, deduce that although the amount of energy is sufficient, the conduction coefficient is not enough and turbulence will produce the wrong entropy and metallicity profiles.

In this proceedings, we shall present a novel mechanism of gravitational heating of the central halo gas by the hydrodynamic interactions between cold clumps of accreted gas and the halo gas (Dekel & Birnboim 2008) and (Birnboim & Dekel 2009, in preparation). The structure of this proceeding paper is as follows: First (section 2.) we show that the accreting gas carries a sufficient rate of energy to compensate for the cooling. Then we model infalling cold clumps, and study the physical processes of their interaction with the diffuse gas, instabilities and survivability (section 3.). Using this model, we study the valid parameter space of these clumps (section 4.1.). We further use these insights to construct a sub-grid model for 1D hydrodynamic simulation and present simulations of a cluster with and without such clumps (section 4.2.). Finally we discuss possible origins of these clumps, and summarize (section 5.).

2. Energetics

Gas falling from infinity to the virial radius will carry specific energy that correspond to the amount needed for heating itself to the virial temperature. Here we assume that because the gas is clumpy, it can penetrate further inwards than the virial radius, deeper into the potential well and release more energy. For an NFW (Navarro et al. 1997) halo profile with typical cluster concentration (Bullock et al., 2001), gas penetrating to 0.1\( R_{\text{vir}} \) will release \( \sim 3.5 \) times the energy it would at \( R_{\text{vir}} \) (Dekel & Birnboim 2008). The baryonic profile is a generalized NFW model (see eq. 4 in 2008) with a core (\( \alpha = 0 \)) that is perhaps indicated by observations (Donahue et al. 2006) and hydrodynamic simulations (Faltenbacher et al. 2007; Kaufmann et al. 2008)

Figure 1, left, shows a comparison between the global cooling rate (using Sutherland & Dopita 1993, and \( Z = 0.3Z_{\odot} \)) and the heating rate assuming accretion rate by Neistein et al. (2006); Birnboim et al. (2007), diffuse baryonic fraction \( f_{b} = 0.05 \) and clump fraction of \( f_{c} = 0.05 \). The Heating/Cooling ratio becomes positive for \( M_{\text{vir}} \geq 10^{13}M_{\odot} \) so the gas accreted as clumps to clusters

\[ \text{In later sections we will use a hydrodynamic simulation for the cluster formation and the need to assume a profile will become moot}\]
Gravitational heating, clumps, overheating

is sufficient to counter the cooling. For clusters of $10^{15} M_\odot$, there is an overabundance of energy of two orders of magnitude, much larger than typical energy emission rates from AGNs.

Figure 1. Left: Heating/Cooling rate as a function of virial mass for the fiducial case (blue, solid line): $f_b = 0.05$, $f_c = 0.05$, $Z = 0.3 Z_\odot$ and $R_{\text{final}} = 0.1 R_{\text{vir}}$ at $z = 0$. Similar lines for $z = 2$ (upper, dashed green) and for $f_b = 0.075$, $f_c = 0.025$ (lower, dashed green) are also presented. Below $M_{\text{vir}} = 10^{12} M_\odot$, the halo gas cannot be hot (Birnboim & Dekel 2003; Dekel & Birnboim 2006) and no hydrodynamic drag is possible. Right: allowed parameter space for clump heating mechanism on $m_c/M_v$ space at $z = 0$, $Z = 0.3 Z_\odot$ and $f_c = f_b = 0.05$: in white areas Heating/Cooling $(H/Q) > 1$. The black lines show $H/Q$ of 3, 10, 30. The yellow areas have $H/Q < 1$ and red areas are susceptible to Bonnor-Ebert instability. Both figures are originally from Dekel & Birnboim (2008) by the kind permission of John Wiley & Sons Ltd.

3. Physics of cold clumps

Drag forces. The clumps in focus here are cold ($10^4 K$) gaseous clumps, in hydrostatic equilibrium with their surrounding hot gas. The hydrodynamic drag force is:

$$ f_{\text{drag}} = -\frac{\pi}{2} C_d \rho g V_r^2 r_c^2 \hat{V}_r, $$

with $\rho_g$ the ambient gas density, $V_r$ the relative velocity between the clump and the ambient gas, $\hat{V}_r$ is the radius vector of that velocity, and $r_c$ is the radius of the clump. $C_d$ is the drag coefficient, and for gaseous spheres it is of order of 1 for subsonic velocities and supersonic velocities alike. The drag force always act to decrease the kinetic energy of the clump. This energy is

$^2$While the equation of drag is the same for the subsonic and supersonic case, the dissipation mechanism is different. For subsonic motions the sphere creates turbulence which dissipates to heat. For supersonic motions a bow shock travels in front of the sphere heating the ambient gas. In the transonic regime $C_d$ can increase to a factor of a few, but then decrease back to $C_d \sim 1$ for supersonic and subsonic velocities.
converted into thermal energy of the hot gas (see Murray & Lin (2004) and discussion in Dekel & Birnboim (2008)). The rate of heating is $\frac{dE}{dt} = f_d |V_r|$, and the trajectory of the clumps tends to become radial because the velocity in the radial direction is replenished by the gravitational force, but the tangential velocity decreases monotonically. From eq. 1 it is evident that the deceleration is more efficient for smaller clumps, larger velocities, and larger gas density.

**Survivability of clumps.** Kelvin Helmholtz (KH) instabilities cause the clump to disintegrate after it repels its own mass in ambient gas (Murray & Lin 2004). The clumps disintegrate into a few pieces (typically 2), each piece undergoing the same drag forces and KH instability. If the clumps are too small, conduction will cause the clump to expand and disintegrate. The conduction coefficient $f_s$ (Spitzer 1962), depends strongly on the unknown magnetic properties of the gas and is assumed here to be $0.01 \leq f_s \leq 0.1$. A discussion on that is present in Maller & Bullock (2004). If, however, the clump is too massive, it will become gravitationally unstable and collapse under its own gravity and the external pressure. The Bonnor-Ebbert mass (Ebert 1955; Bonnor 1956) sets the maximal allowed clump mass.

**Death of clumps.** As clouds fragment and become more susceptible to conduction and small scale turbulence, heat from the surrounding hot gas will flow into the cold clump residue, heating it until it joins its surrounding halo. In this final stages, the clump “steals” energy from the hot gas, cooling it. The net effect, however, is heating because the clumps spends 3.5 times than it ultimately absorbs. This cooling has been taken into effect in the static and dynamic tests in the following sections. In cases where clumps exceed the Bonnor-Ebert mass (Jeans mass with external pressure confinement) the clump gas would turn into star without such “theft”.

**Local and global instabilities.** The cooling rate of the baryons, in the Bremsstrahlung regime scales (for isobaric gas) scales as $\frac{d\rho g}{dt} \sim \rho^2 T^{1/2} \sim \rho^{1.5}$. Field (1965) noted that heating must be scale with a power at least as large for the gas to be cooling-stable. However, the clump heating scales like $\rho g$ (eq. 1). This means that, assuming some parcel of gas that is initially in heating/cooling equilibrium, if gas is perturbed such that the cooling becomes slightly faster than the heating, the gas contracts, causing the discrepancy between heating and cooling to increase even further. If, on the other hand, heating is larger than the cooling, the gas will expand, causing the cooling to become even less efficient with respect to the heating. As we will show in section 4.2., the later case actually occurs, and causes some of the shells to heat and expand more than their surrounding. This creates entropy inversions, which are regulated by convection. This local instability, as it turns out, does not effect the global stability of the halo: the location of the virial shock, the temperature, and the dynamics of the gas throughout the halo does not change as a result of this heating (see section 4.2.).

**Origin of clumps.** In section 4.1. we show that allowed masses for the gaseous clumps is between $10^5 - 10^8 M_\odot$. Mechanisms for formation of such clumps are still under investigation. The virial temperature that corresponds to mini-halos with baryonic mass $\leq 10^8 M_\odot$ is smaller than $10^4 K$ so even if dark matter mini-halos are formed, they cannot retain their gas after reionization. Cooling instability, especially in filaments or partly shocked gas at the edges of
the clusters \((T \sim 10^5 - 10^6 K)\) can potentially create such clumps. These clumps can also be produced within halos \cite{Maller & Bullock 2004}. No hydrodynamic simulation today has the resolution to investigate the formation of such clumps.

4. Numerical tests and simulations

4.1. Static Monte-Carlo simulations

The drag force equation and clump fragmentation have been incorporated into a Monte-Carlo simulation of a static NFW halo with a baryonic core \cite[see][]{Dekel & Birnboim 2008} for details). In these simulations the initial trajectories of 4000 clumps were drawn from reasonable distributions, and the heating rates were calculated as a function of radius, following fragmentation, evaporation, conduction, local Bonnor-Ebert masses, as well as dynamical friction. In some cases, a dark matter (DM) counterpart for the clumps was initially assumed. The DM subhalo generally gets ripped from the baryonic part during the first passage near the center, because the drag forces act on the baryons alone, and introduce forces between the DM and the baryons. Figure 1, right, describes results of the Monte-Carlo approach by mapping the allowed range in \(m_c/M_v\) parameter space. For halos above \(10^{13} M_\odot\), and clumps between \(10^5 - 10^8 M_\odot\), the heating rate is larger than the cooling rate, for the fiducial values described in the caption.

4.2. 1D hydrodynamic simulations

The evolution of galaxy and cluster halos from initial perturbation has been studied with a 1D spherical Lagrangian hydrodynamic simulation with 1D dark matter shells that evolve separately through the baryonic shells, cooling and angular momentum \cite{Birnboim & Dekel 2003, Dekel & Birnboim 2006, Birnboim et al. 2007}. The effect of clump heating was added to the simulation as a sub-grid model of “clump shells” by assigning many clumps to shells similar to dark matter shells and allowing them to interact with the baryons via the drag equation and internal energy equation of the baryons. Each clump shell contains \(n\) clumps, and once the conditions for disintegration of clumps are met the clump mass of that shell is divided by 2 and \(n\) is multiplied by 2. Once clumps are killed (their mass drops below the conduction lower limit, \(10^4 M_\odot\)) the mass of the clump shell is added in situ to the baryonic shell overlapping the clump shell, and the new temperature is calculated by mixing the hot halo gas with the cold shell gas. Since the gas is cooling/heating unstable (see section 3.), shells heat and expend in an unstable manner. To deal with this physical situation, gaseous shells are split into two when they become larger than their surrounding shells (AMR), and physical convection is modeled by mixing length theory \cite{Spiegel 1963} was implemented.

Figure 2 shows results of three such simulations with similar initial profile that leads to a \(3 \cdot 10^{14} M_\odot\) halo at \(z = 0\). In the first, no clumps are added, the CD galaxy grows to \(3 \cdot 10^{12} M_\odot\) and the star formation rates remains larger than \(100 M_\odot/yr\) since \(z = 1\). By assuming that 10% of the baryons are accreted as clumps the size of the CD galaxy is reduced to \(1.5 \cdot 10^{12} M_\odot\), star formation rate reduced to virtually zero. The third simulation is similar to the second, except for mixing length model is used to smooth over the local instabilities. In all three
Figure 2. Results of a 1D Hydrodynamic simulation of a $3 \cdot 10^{14} M_\odot$ halo with $f_c + f_b = 0.1$ and $Z = 0.3 Z_\odot$. **Left**: Flow lines of Lagrangian shells (grey thin lines, with temperature colormap. Top panel - no clumps, second panel - $f_c = 0.01$ and $m_c = 10^7 M_\odot$, third panel - $f_c = 0.01$, $m_c = 10^7 M_\odot$ with mixing length model for convection (“clump+convection”), bottom panel - mass evolution of the central galaxy (red; solid - “no clumps”, green; long-dashed - $f_c = 0.01$, blue; dashed - “clump+convection”). **Right**: Radial profiles at $z = 0$ of the “no clump” (red; solid) and “clump+convection” (blue; dashed) simulations. top - entropy, middle - temperature. Bottom - H/C for the “clump+convection” case.

Simulations the virial mass and virial shock radius did not change indicating that the heating does not effect the global stability of the halo. The shape of the entropy profile and the central values are consistent with those of cooling flow profiles of Donahue et al. (2006). The hydrodynamic code and simulation results are described in detail in (Birnboim & Dekel 2009, in preparation)

5. summary

We have shown that a sufficient amount of energy is released in the gravitational accretion to solve the overcooling problem of clusters (larger than $M_{vir} \geq 10^{13} M_\odot$), if we assume that some part of the baryons penetrates to the inner parts rather that being stopped at the virial radius. The coupling between the incoming accreted mass and the ambient gas is achieved by assuming that the accreted baryons includes gaseous cold clump, that penetrate through the virial shock and heat the gas via hydrodynamic drag. A parameter space survey indicates that for halos larger than $10^{13} M_\odot$ and clump masses in the range $10^5 \leq m_c \leq 10^8 M_\odot$, clump heating can potentially solve the overcooling problem. The dynamic response of cluster halos to clump heating, cooling and mass deposition in the inner parts in then examined. For the set of values $M_{vir} = 3 \cdot 10^{14} M_\odot$, $m_c = 10^7 M_\odot$, $f_b + f_c = 0.1$, $f_c = 0.01$, the resulting entropy and temperature profiles match typical observed cooling flow clusters reasonably well. The physical processes discussed here are already included in
3D hydrodynamic simulations but we note that to simulate the drag and the formation of such clumps each $10^7 M_\odot$ clump need to be well resolved, which is typically not the case for $10^{15} M_\odot$ clusters.

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