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Gravo-thermodynamics of the intracluster medium: Negative heat capacity and dilation of cooling time scales

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ABSTRACT

The time scale for cooling of the gravitationally bound gaseous intracluster medium (ICM) is not determined by radiative processes alone. If the ICM is in quasi-hydrostatic equilibrium in the fixed gravitational field of the dark matter halo then energy losses incurred by the gravitational potential energy of the gas should also be taken into account. This "gravitational heating" has been known for a while using explicit solutions to the equations of motion. Here, we re-visit this effect by applying the virial theorem to gas in quasi-hydrostatic equilibrium in an external gravitational field, neglecting the gravity of the gas. For a standard NFW form of halo profiles and for a finite gas density, the response of the gas temperature to changes in the total energy is significantly delayed. The effective cooling time could be prolonged by more than an order of magnitude inside the scale radius (r_s) of the halo. Gas lying at a distance twice the scale radius, has negative heat capacity so that the temperature increases as a result of energy losses. Although external heating (e.g. by AGN activity) is still required to explain the lack of cool ICM near the center, the analysis here may circumvent the need for heating in farther out regions where the effective cooling time could be prolonged to become larger than the cluster age and also explains the increase of temperature with radius in these regions.

1. Introduction

Clusters of galaxies are the most massive virialized objects observed in the Universe. Their potential depths correspond to virial temperatures of 1–10 keV (10^7–10^8 K) and the baryon number density in the inner regions could be as high as 0.1 cm^{-3} (e.g. Vikhlinin et al., 2005; Pointecouteau et al., 2005). For these temperatures and densities, radiative losses are expected to the bring the temperature in the central regions down to $\gtrsim 10^4$ K within the available time. Yet in none of the observed clusters does the temperature drop to the level dictated by cooling alone. The absence of significant amounts of cold gas in the cores of massive clusters is a major puzzle posed by X-ray observations of massive clusters (e.g. Peterson et al., 2001). Hence, efficient heating mechanisms must operate at the cores of all cooling clusters. The most popular mechanism for suppressing cooling is energy released by an AGN in the central cluster galaxy (cf. Quilis et al., 2001; Babul et al., 2002; Kaiser and Binney, 2003; Dalla Vecchia et al., 2004; Roychowdhury et al., 2004; Voit and Donahue, 2005; Nipoti and Binney, 2005, and references therein) or by multiple AGN activity in all galaxies in the cores of clusters (Nusser et al., 2006; Eastman et al., 2007; Nusser and Silk, 2008). Over-pressurized ejecta from the AGN transform into hot bubbles that eventually reach pressure equilibrium with the ICM and proceed to rise buoyantly away from the center. These bubbles could heat the ICM by means of shock waves generated as they expand to reach the ICM pressure (Nusser et al., 2006), and by drag forces when they become buoyant (e.g. Churazov et al., 2001). Mechanical activity near the center could also generate sound waves which are believed to eventually dissipate their energy in the ICM (Pringle, 1989; Ruszkowski et al., 2004; Heinz and Churazov, 2005; Fujita and Suzuki, 2005; Sanders and Fabian, 2007). To balance cooling in a cluster of X-ray luminosity of $L_x \sim 10^{44}$ erg s^{-1}, a central AGN must produce $\sim 10^{60}$ erg over the entire life-time of the cluster. For the most massive clusters (potential depths corresponding to velocity dispersions >500 km/s) the required heating could be more than an order of magnitude larger than the observed range of AGN energy output in galaxy clusters, based on the pV content of X-ray cavities (e.g. Best et al., 2007). This is not too worrying since weak shocks could certainly compensate for the missing energy needed to balance cooling. For less massive clusters the pV energy is sufficient to balance cooling (e.g. Bîrzan et al., 2004). The challenge, however, is to arrange for efficient energy transport from the AGN over the entire cooling core, or out to distances of up to ∼100 kpc.

The temperature in the inner regions increases gradually as we move away from the center. At first, this behavior may seem reasonable since the radiative cooling becomes more efficient nearer to the center. But, the cooling time is significantly shorter than the cluster age over a significant part of the inner regions and the ICM had ample opportunity to cool to very low temperatures

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(e.g. Fig. 12 in Wise, McNamara and Murray, 2004). So why is there not a temperature plateau extending over the region where the cooling time is shorter than the cluster age? One explanation might be that, on account of the lower density, heat conduction is more significant as we move away from the center. However, heat conduction is not universally important in these regions (e.g. Wise, McNamara and Murray, 2004). Here show that the cooling time could significantly be modified when the potential energy of the ICM in the dark halo is taken into account. We will use a version of the virial theorem to show that the potential energy will absorb some of the energy loss incurred by the system. In some cases the potential energy will decrease by an amount larger than the actual loss, forcing the system to compensate the energy difference by increasing its thermal energy. This is the case of negative heat capacity. This phenomenon is sometimes referred to as gravitational heating and has been discussed previously (e.g. Fabian and Nulsen, 1977) and is evident in numerical simulations of the ICM. However, the description in terms of the virial theorem as is done here is new and offers a simple analysis for assessing the dependence of the effective cooling time on the assumed halo profile.

2. The virial theorem

Hereafter we will assume spherical symmetry and denote by r the distance from the center. Let $\rho_g(r)$, $u(r)$, and $P=(\gamma-1)\rho_g u$ be, respectively, the gas density, energy per unit mass, and pressure, where γ is the adiabatic index. The temperature, T, is related to u by $u=k_BT/(\gamma-1)/m$, where m is the mean particle mass and k_B is the Boltzman constant. We assume a gas obeying the equation

$$\rho_g g-\frac{dP}{dr}=0, \tag{1}$$

where g is the gravitational force field per unit mass. This equation is applicable in quasi-hydrostatic equilibrium so that the acceleration of the gas is negligible. Multiplying (1) by r and integrating over the volume from $r=0$ to R_0 gives the virial theorem

$$3(\overline{P}-P_0)V+W=0, \tag{2}$$

where $V=(4\pi/3)R_0^3$, $P_0=P(R_0)$ is the external pressure, $\overline{P}=4\pi\int_0^{R_0} dr r^2P(r)/V$ is the average pressure inside R_0, and the gravitational term, W, is

$$W=4\pi\int_0^{R_0} r^3\rho_g g(r)dr. \tag{3}$$

A more general derivation which includes gas motions could be found in Ostriker and McKee (1988). The energy of the system in the volume V is written as the sum of the thermal energy $\overline{P}V/(\gamma-1)\propto Nk_BT$ (N is the total number of particles) and the gravitational potential energy, U

$$E=U+\frac{\overline{P}V}{\gamma-1}, \tag{4}$$

where

$$U=4\pi\int_0^{R_0}\rho_g\Phi r^2 dr, \tag{5}$$

and the system is assumed to reside in a static external gravitational potential Φ and neglected gravity of the gas.

From the virial theorem (2) and the energy Eq. (4) we obtain global relations between infinitesimal variations (denoted by the prefix δ) in the total energy, E, the thermal energy E_{th}, V, W and U. Keeping a constant external pressure P_0 these relations are

$$\delta W=3P_0\delta V-3(\gamma-1)\delta E_{th}, \tag{6}$$

and

$$\delta E=\delta U+\delta E_{th}, \tag{7}$$

where we have used the expression $E_{th}=\overline{P}V/(\gamma-1)$ for the thermal energy. These relations must hold for any change in the state of the system. For radiative losses, the energy loss in time δt is $\delta E=n_e\Lambda(T)\delta t$ where n_e is the electron number density and Λ is the cooling rate. Even if this energy is extracted initially from the thermal part, E_{th}, subsequent evolution of the system will establish the relations (6) and (7). We are working under the assumption of quasi-hydrostatic equilibrium so that any bulk motions generated during this process are neglected. In any case, if dissipation is important then significant gas motions will be converted into heat, restoring the above relations.

We are set now to derive a relation between δE and δE_{th}. We write $\delta V=(\delta V/\delta W)\delta W$ in the virial relation (6) to obtain

$$\delta W=\frac{3(\gamma-1)}{3P_0\frac{\delta V}{\delta W}-1}\delta E_{th}. \tag{8}$$

Writing $\delta U=(\delta U/\delta W)\delta W$ and $\delta V=(\delta V/\delta W)\delta W$ in the relation (7) while taking δW from (8) we get

$$\delta E=\mathscr{C}\delta E_{th}, \tag{9}$$

where

$$\mathscr{C}=1+\frac{\delta U}{\delta W}\frac{3(\gamma-1)}{3P_0\frac{\delta V}{\delta W}-1}. \tag{10}$$

The quantity $\mathscr{C}$ gives the ratio of the heat capacity to the standard thermodynamic heat capacity computed without gravity. Hence we call $\mathscr{C}$ the relative heat capacity (RHC). The sign of $\mathscr{C}$ determines whether the thermal energy, E_{th}, and hence the temperature, $T\propto E_{th}/N$, will increase or decrease as a result of changing the total energy, E. If $\mathscr{C}<0$ holds, then the heat capacity is negative, i.e. the temperature increases when we extract energy from the system. For $P_0=0$, the condition $\mathscr{C}<0$ implies

$$\frac{\delta U}{\delta W}>\frac{1}{3(\gamma-1)}. \tag{11}$$

For positive RHC, $\mathscr{C}>0$, the response time of the gas temperature to variations in its energy is prolonged by a factor $\mathscr{C}$. For example, the effective cooling time is $\mathscr{C}t_{cool}$ where $t_{cool}\sim k_BT/(n_e\Lambda)$ is the usual radiative cooling time.

3. Applications to various forms of halo gravitational potentials

We begin with the calculation of the RHC, $\mathscr{C}$, for power-law potentials of the form, $\Phi=A/r^n$ so that $g=An/r^{n+1}$, where $n\neq0$ and A are constants. The constant A is negative for $n>0$ and positive otherwise. In this case $W=nU$ and $\delta U/\delta W=1/n$ and for $P_0=0$ we have

$$\mathscr{C}=1-\frac{3}{n}(\gamma-1). \tag{12}$$

Thus $\mathscr{C}$ is negative for

$$0<n<3(\gamma-1), \tag{13}$$

which gives $0<n<2$ for $\gamma=5/3$. To estimate the RHS, $\mathscr{C}$, for a non-vanishing external pressure, P_0, we need the quantity $\delta W/\delta V$ which depends on gas density profile, ρ_g, in the system. We work here with a power-law density profile of the form, $\rho_g=B/r^\alpha$ and we compute $\delta W/\delta V$ under variations of the external radius R_0 assuming that the index α and the total mass, M_0, inside R_0 remain constant. Since $M=4\pi\int r^2B/r^\alpha dr$ we get

$$B=\frac{3-\alpha}{4\pi}MR_0^{\alpha-3}. \tag{14}$$