Strong Turbulence in the Cool Cores of Galaxy Clusters: Can Tsunamis Solve the Cooling Flow Problem?

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ABSTRACT

Based on high-resolution two-dimensional hydrodynamic simulations, we show that the bulk gas motions in a cluster of galaxies, which are naturally expected during the process of hierarchical structure formation of the universe, have a serious impact on the core. We found that the bulk gas motions represented by acoustic-gravity waves create local but strong turbulence, which reproduces the complicated X-ray structures recently observed in cluster cores. Moreover, if the wave amplitude is large enough, they can suppress the radiative cooling of the cores. Contrary to the previous studies, the heating is operated by the turbulence, not weak shocks. The turbulence could be detected in near-future space X-ray missions such as ASTRO-E2.

Subject headings: cooling flows—galaxies: clusters: general—waves—turbulence—X-rays: galaxies: clusters

1. Introduction

Clusters of galaxies are the largest gravitationally bound and collapsed systems in the universe. They are filled with X-ray emitted hot gas with the temperature of $T \sim 2–10$ keV. High-resolution X-ray observations have revealed that the hot gas in many cluster cores is not smoothly distributed (e.g. Fabian et al. 2001; Sanders & Fabian 2002). Here, we define the cluster cores as the dense regions within $\sim 30–300$ kpc from the cluster centers. The

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complicated structures are often attributed to activities of active galactic nuclei (AGNs). In fact, bubbles of high energy particles have been found in some clusters (e.g., Fabian et al. 2000; McNamara et al. 2000; Blanton et al. 2001), which is the evidence that AGNs affect the surrounding hot gas. However, the complicated structures have also been observed in clusters in which AGNs are not active at the centers (e.g., Furusho, Yamasaki, & Ohashi 2003). In the outer regions of the cores, edge-shaped discontinuities in the gas density and temperature (‘cold fronts’) are often found (e.g., Markevitch, Vikhlinin, & Mazzotta 2001). They may be attributed to the ‘sloshing’ of the gas in the cluster gravitational potential well, although the origin remains an open question (Markevitch et al. 2001; Churazov et al. 2003).

From the above observations, one may think of complex gas motion, that is, turbulence in the cores. Actually, turbulence is expected to be prevailing in cluster cores. Although it has not yet directly been observed in X-rays (but see Churazov et al. 2004), cold gas \((T \sim 10^4 \text{ K})\) moving with the velocity of 100–1000 km s\(^{-1}\) has been observed. If the ambient X-ray gas did not move with the cold gas, the latter would immediately mix with the former (Loewenstein & Fabian 1990). Moreover, the turbulence may be playing an important role in heating of the cluster cores. It had been expected that the gas in cluster cores cools by radiating away its thermal energy, which induces gas motion toward the cluster centers (‘cooling flows’; Fabian 1994). However, X-ray spectra have revealed that the mass of the cooling gas is far smaller than that expected from this model (Makishima et al. 2001; Peterson et al. 2001; Kaastra et al. 2001; Tamura et al. 2001). The turbulence may transport thermal energy from the outside of the cluster cores, and may balance the radiative cooling of the cores (Cho et al. 2003; Kim & Narayan 2003; Voigt & Fabian 2004). However, the actual mechanism that creates the turbulence has not been understood.

The scenario we newly propose here is that the core turbulence is created by bulk gas motions, which are naturally produced in the X-ray hot gas in clusters. Cosmological numerical simulations have shown that clusters are knots of larger-scale filaments in the universe (Burns 1998). Along the direction of the filaments, small clusters (or galaxies) successively fall into a cluster, which increases the cluster mass. The simulations have also shown that the infall velocities of the smaller clusters are more than 1000 km s\(^{-1}\) (Burns 1998). The interactions of the hot gas and dark matter between the clusters should produce a large-scale gas motion; the velocity is typically \(\gtrsim 300 \text{ km s}^{-1}\) and sometimes reaches \(\gtrsim 1000 \text{ km s}^{-1}\) (Burns 1998). The cluster cores are exposed to these violent gas motions; this would create possible turbulence and the complicated structures observed in the cores even if there are no AGN activities.

In order to test this scenario, we performed two-dimensional high-resolution hydrody-
namic simulations to follow the long-term evolution of the core in ‘a stormy cluster’ for the first time.

2. Models

Since we are interested in the cluster core and we need resolution high enough to resolve turbulence, we limited the calculations to the central region of a cluster (within \( \sim 300 \) kpc from the cluster center). These simulations were performed using a nested grid code (Matsumoto & Hanawa 2003), and the coordinates are represented by \((R, z)\). While the resolution near the outer boundary is 1.4 kpc, that at the cluster center is 22 pc. Free boundaries were chosen. Thermal conduction, viscosity, magnetic fields, and the self-gravity of gas were ignored. Radiative cooling is included. We adopted a cooling function for the metal abundance of 0.3 solar. The gas is isothermal and the temperature is 7 keV at \( t = 0 \). The fixed gravitational potential and the initial gas distribution are the same as those in Fujita, Suzuki, & Wada (2004b).

We approximated the bulk gas motions in a cluster by plane wave-like velocity perturbations represented by \( \delta v = \alpha c_s \sin(2\pi c_s t/\lambda) \) at \( z = -345 \) kpc, where \( c_s \) is the initial sound velocity, and \( \lambda \) is the wave length. This assumption comes from the idea that continuous infall of matter and small clusters along a large-scale filament should create velocity perturbations in a particular direction. The factor \( \alpha \) is a free parameter and \((R, z) = (0, 0)\) is the cluster center. We studied the perturbations with \( \alpha \) and \( \lambda \) shown in Table 1. Note that cosmological numerical simulations suggested that the velocity of the hot gas is about 0.2–0.3 \( c_s \) or larger even when a cluster is relatively relaxed (Nagai, Kravtsov, & Kosowsky 2003; Motl et al. 2004). Moreover, it is expected that the scale of bulk gas motion in a cluster is \( \sim 100 \) kpc or larger (Roettiger, Stone, & Burns 1999; Motl et al. 2004). Therefore, we think that the parameters we took are reasonable. However, since the large bulk motions in a cluster do not always generate large amplitude acoustic-gravity waves, our model may be appropriate for clusters undergoing hierarchical structure formation or similar violent events. Since the energy input rate through waves per unit area is given by \( \sim (1/2) \rho \alpha^2 c_s^3 \), where \( \rho \) is the gas density, the integrated input rate for \( R < 150 \) kpc at \( z = -345 \) kpc is \( 1.2 \times 10^{44}(\alpha/0.3)^2 \) ergs s\(^{-1}\) for our model cluster. On the other hand, at \( t = 0 \), the X-ray luminosity of the gas for \( R < 100 \) kpc and \(|z| < 100 \) kpc is \( 2.4 \times 10^{44} \) ergs s\(^{-1}\) and is comparable to the wave energy input rate.
3. Results

In Figures 1 and 2, we present the temperature distributions for $\alpha = 0.3$ and $\lambda = 100$ kpc; the velocity perturbations propagate upwards as acoustic-gravity waves, which were called ‘tsunamis’ in Fujita et al. (2004b). Since the velocity amplitude is relatively large, the waves steepen and become weak shocks as shown in one-dimensional simulations (Fujita et al. 2004b). Because of the pressure coming from the momentum of the waves, the coolest and densest gas noticeably shifts from the cluster center at $t \gtrsim 0.7$ Gyr and the shift is clearly seen at $t = 1$ Gyr (Fig. 1). While the position of the coolest gas is at $z \sim 25$ kpc (Fig. 1), that of the densest gas is $z \sim 10$ kpc. The difference of the positions is made by the wave just passed (Fig. 1); the gas slightly deviates from pressure equilibrium there. Comparing the result of $\alpha = 0.3$ with that of $\alpha = 0$, we found that the gravitational energy of the gas for the former is larger than that for the latter by $2.1 \times 10^{60}$ ergs for $R < 150$ kpc and $|z| < 345$ kpc at $t = 1$ Gyr. The energy increase is smaller than the energy input by waves during the first one Gyr for $R < 150$ kpc ($3.9 \times 10^{60}$ ergs), suggesting that a part of the injected energy is used to produce the shift of dense gas. After that, radiative cooling proceeds and the core region becomes cooler and denser. Since waves no longer sustain the cooling core, the core falls in the potential well of the cluster. During the fall, Rayleigh-Taylor (RT) and Kelvin-Helmholtz (KH) instabilities develop around the core. They non-linearly develop, and turbulent motion is eventually formed in and around the core as seen in Figure 2, which shows the temperature distribution at $t = 3.3$ Gyr. The cool core oscillates around the cluster center, and temperature jumps are formed (Fig. 2a). Associated with these temperature jumps, gas density also has discontinuities. Small cool and dense blobs randomly moving in the core cause new RT and KH instabilities around them, and smaller eddies are generated (Fig. 2b). For the models of $\alpha = 0.3$ and 0.5, the turbulence is maintained until our calculations are stopped at $t \sim 5$ Gyr. It is interesting that the turbulence presented here is naturally caused even by the regular, wave-like, linear perturbations. No irregular triggers, which are usually essential for initiating or maintaining turbulence, are necessary.

In Table 1, we present the time when the gas temperature in any of the numerical grid points reaches zero ($t_{\text{cool}}$). The gas cooling is suppressed by heat transport through turbulent mixing, especially when $\alpha$ is large. In other words, in addition to the wave input energy (see §2), the thermal energy transported from the outside of the core is used to prevent the core from cooling.

We note that although there were several studies treating core heating by acoustic-gravity waves, the mechanism of the heating presented here is completely different from that proposed in the previous studies. In those previous studies, based on the analytical
approach (Pringle 1989) or one-dimensional numerical simulations (Fujita et al. 2004b), it was predicted that weak shocks evolved from acoustic-gravity waves directly heat the cluster core, while in this study the turbulence is the major player of the heating. Since our simulations are multi-dimensional, the results should be much more realistic than those of the previous studies. In fact, since turbulence is essentially multi-dimensional, those previous studies were not able to directly treat the turbulence and complicated structures of the cores. Even with multi-dimensional simulations, the turbulent heating could not be found if the resolution were not high enough.

4. Discussion

The present results show that the turbulence starts to develop after the core becomes dense through cooling. Before that, waves pass the cluster center without much changing the gas structure. Thus, we predict that this mechanism of turbulence generation works only for clusters with dense and cool cores, which had been called ‘cooling flow clusters’. Since the turbulence is spatially limited to the cool core, it does not totally mix the hot gas in a cluster. Thus, as long as violent mergers of clusters with comparable masses, which completely destroy the central gas structures of the clusters, do not happen, the metal abundance excess observed in cluster cores (e.g. Tamura et al. 2001) would not completely be erased.

Because of the turbulent motion, the fine structures of the core are not steady. Our simulation results sometimes show fine structures similar to the peculiar structures observed in clusters such as A1795, Centaurus, and 2A 0335+096 (Fabian et al. 2001; Sanders & Fabian 2002; Mazzotta, Edge, & Markevitch 2003). The temperature jumps seen in Figure 2a may correspond to the ‘cold fronts’ observed in some clusters. The bulk gas motion in clusters would result in the formation of acoustic-gravity waves and the weak shocks as shown above. Direct observations of the waves may be difficult unless the wave fronts are almost parallel to the line of sight. In A133, however, a weak shock just passing through the core has been observed (Fujita et al. 2004a).

The maximum velocity of the turbulence in a cluster core is $\gtrsim 300 \text{ km s}^{-1}$ for $\alpha = 0.3$. With a high spectral resolution detector like the X-ray satellite ASTRO-E2, the turbulence in cluster cores could be detected in the near future. If turbulence is being developed, the metal lines in the X-ray spectra would have very complicated features owing to the gas motion (Inogamov & Sunyaev 2003). On the other hand, turbulence could also be created by AGN activities, especially by the buoyant motion of AGN-origin bubbles. The lifetime of the eddies associated with the bubble motion is $t_{edd} \sim L_{bub}/v_{bub}$, where $L_{bub}$ and $v_{bub}$ are
the size and velocity of a bubble, respectively. For the Virgo cluster, for example, the size of the observed bubbles is \( \sim 10 \) kpc, and the predicted velocity of a bubble is \( \sim 400 \text{ km s}^{-1} \) (Churazov et al. 2001). Thus, the lifetime of the eddies is \( t_{\text{edd}} \sim 2 \times 10^7 \) yr, which is much shorter than the lifetime of the bubble itself (\( \sim 10^8 \) yr; Churazov et al. 2001). This means that turbulence is unlikely to exist in a cluster core without AGN-origin bubbles. Thus, if turbulence is detected in such a core, it could be associated with the bulk gas motions outside of the core.

Our model predicts that cooling of a cluster core is more suppressed for larger velocity amplitude. The suppression should also work in smaller objects such as groups of galaxies and elliptical galaxies because their overall structures are similar to those of clusters of galaxies (Moore et al. 1999), and we expect that the bulk gas motions and turbulence are excited in them by the same mechanism presented here. This is in contrast with the suppression by thermal conduction that does not work in the smaller objects because of their low temperatures (Voigt & Fabian 2004).

Finally, we note the limitations of our model. First, we approximated the bulk gas motions by waves with constant amplitude and length, and direction for propagation is also assumed to be fixed, but in reality all these conditions should be changed during formation and evolution of clusters. Even bulk gas motions that are not represented by regular waves considered here could cause the motion of the cool cores and produce turbulence through RH and KT instabilities. Moreover, it is likely that waves come from several directions corresponding to large-scale filaments. These effects should be ultimately studied by fully three-dimensional, ultra-high-resolution cosmological simulations, although the basic mechanism initiating the turbulence would not be different from the one in the two-dimensional case here. Second, we did not include the heating by turbulent dissipation, AGNs, and thermal conduction. If they are effective as thermal energy sources, the wave energy required to suppress the cooling of a core would be smaller than that we predicted. Note that the turbulence may tangle magnetic fields and reduce an effective conduction rate. However, Narayan & Medvedev (2001) indicated that chaotic magnetic fields do not much reduce the conduction rate. Thus, we may need to follow the evolution of magnetic field lines when we include the effect of thermal conduction. Third, we fixed the gravitational potential of a cluster. A change in the potential may also shift the cool gas core from the gravitational center of the cluster, which may lead to the motion of the core and the development of turbulence (Ricker & Sarazin 2001). Fourth, we assumed a two-dimensional axi-symmetric geometry. This might affect development and structure of turbulence. It would be expected that cascade processes of eddies is different in full three-dimensional turbulence. Interaction between the turbulence and plane-waves in three-dimensions should be also clarified in future simulations.
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REFERENCES


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Table 1. Wave parameters

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<th>$\alpha$</th>
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Fig. 1.— The temperature distribution of a cluster core at $t = 1.0$ Gyr. The periodic input waves are seen in Fig. 1a as discontinuities that is nearly parallel to the $R$-axis. The waves propagate upward in these figures. (a) for $z \lesssim 200$ kpc, (b) for $z \lesssim 20$ kpc. Movies are available at http://th.nao.ac.jp/tsunami/index.htm. Note that color bars are different between (a) and (b).
Fig. 2.— The same as Fig. 1 but for $t = 3.3$ Gyr. The arrows in Fig. 2a indicate 'cold fronts'.