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TURBULENCE PRODUCED BY TSUNAMIS IN GALAXY CLUSTERS

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ABSTRACT

Clusters of galaxies are filled with X-ray emitted hot gas with the temperature of T ∼2–10 keV. Recent X-ray observations have been revealing unexpectedly that many cluster cores have complicated, peculiar X-ray structures, which imply dynamical motion of the hot gas. Moreover, X-ray spectra indicate that radiative cooling of the cool gas is suppressed by unknown heating mechanisms (the 'cooling flow problem'). Here we propose a novel mechanism reproducing both the inhomogeneous structures and dynamics of the hot gas in the cluster cores, based on state-of-the-art hydrodynamic simulations. We showed that acoustic-gravity waves, which are naturally expected during the process of hierarchical structure formation of the universe, surge in the X-ray hot gas, causing a serous impact on the core. This reminds us of tsunamis on the ocean surging into an distant island. We found that the waves create fully-developed, stable turbulence, which reproduces the complicated structures in the core. Moreover, if the wave amplitude is large enough, they can suppress the cooling of the core. The turbulence could be detected in near-future space X-ray missions such as ASTRO-E2.

Key words : cooling flows – clusters of galaxies – turbulence – waves – X-rays

I. INTRODUCTION

High-resolution X-ray observations have revealed that the hot gas in many cluster cores is not smoothly distributed. The 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 (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 (Furusho et al. 2003). In the outer regions of the cores, edge-shaped discontinuities in the gas density and temperature ('cold fronts') are often found (Markevitch et al. 2001). They may be attributed to the 'sloshing' of the cool gas in the cluster gravitational potential well, although the origin remains an open question (Markevitch et al. 2001; Churazov et al. 2003).

Turbulence is expected to be prevailing in cluster cores. Although it has not yet directly been observed, cold gas ($T \sim 10^4$ 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). Although the turbulence may be important for the heating of the cluster cores (Cho et al. 2003; Kim & Narayan 2003; Voigt & Fabian 2004), the actual mechanism that creates the turbulence has not been understood.

The above phenomena could be explained at a time by considering acoustic-gravity waves that 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 (Borgani & Guzzo 2001). Along the direction of the filaments, small clusters (or galaxies) successively fall into a cluster, which increases the cluster mass. If the smaller clusters are not too dense and the masses are not comparable to that of the larger cluster, the X-ray hot gas in the smaller clusters is stripped by the ram-pressure from the hot gas in the larger cluster before the smaller clusters reach the center of the large cluster; only the halos of dark matter ('dark halos') can penetrate the center because dark matter is collisionless (Gómez et al. 2002). The stripping should produce acoustic-gravity waves. Some of them propagate toward the center of the larger cluster and interact with the core, which would create the observed structure and possible turbulence in the core.

II. MODELS

In order to test this scenario, we performed two-dimensional high-resolution hydrodynamic simulations to follow the long-term interaction for the first time. Since we are interested in the cluster core and we need resolution high enough to reproduce turbulence, we calculated the evolution of the X-ray hot gas within ∼ 300 kpc from the cluster center. These simulations were performed using a nested grid code (Matsumoto & Hanawa 2003). While the resolution near the outer boundary is 1.4 kpc, that at the cluster center is 22 pc. Radiative cooling is included. The gravitational potential and the initial gas distribution are the same as

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those in a previous study (Fujita et al. 2004c). Free boundaries were chosen. Thermal conduction, viscosity, magnetic fields, and the self-gravity of gas were ignored. We adopted a cooling function for the metal abundance of 0.3 solar. The gas is isothermal and the temperature is 7 keV at $t = 0$.

We gave plane velocity perturbations of the hot gas 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 λ is the wave length. The factor α is a free parameter and $z = 0$ is the cluster center. We studied the waves with α and λ 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 et al. 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 (Motl et al. 2004; Roettiger et al. 1999).

Table 1. WAVE PARAMETERS

α	λ (kpc)	$t_{\rm cool}$ (Gyr)
0		2.2
0.3	100	3.3
0.5	500	4.7

III. RESULTS AND DISCUSSION

The detailed results are shown in Fujita et al. (2004b). In Figures 1 and 2, we present the temperature distributions for $\alpha = 0.3$ and $\lambda = 100$ kpc; waves propagate upwards. Since the wave amplitude is relatively large, the acoustic-gravity waves steepen and become weak shocks as shown in one-dimensional simulations (Fujita et al. 2004c). Because of the momentum of the waves, the coolest and densest gas shifted from the cluster center at $t = 1$ Gyr (Fig.1). 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. Figure 2 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.

In Table 1, we present the time when the gas temperature in any of the numerical grid points reaches zero ($t_{\rm cool}$). The gas cooling is suppressed by heat transfer through the turbulence, especially when α is large. The results presented here are quite different from the

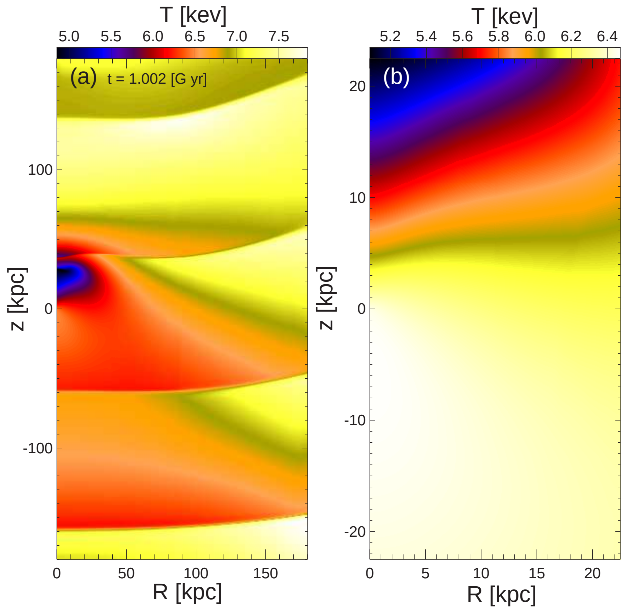

Fig. 1.— The temperature distribution of a cluster core at $t = 1.0$ Gyr. The periodic input waves are seen in Fig.1a as discontinuities that is nearly parallel to the R-axis. The waves propagate upward in these figures. (a) for $z \lesssim 200$ kpc, (b) for $z \lesssim 20$ kpc. Movies are available at http://th.nao.ac.jp/tsunami/index.htm.

predictions based on the analytical approach (Pringle 1989) or one-dimensional numerical simulations (Fujita et al. 2004c), in which weak shocks evolved from acoustic-gravity waves directly heat the cluster core.

The present results show that the turbulence starts to develop after the core becomes dense through cooling. Before that, waves just pass the cluster center and do not change the gas structure. The turbulence is spatially limited to the cool core. Thus, it does not totally mix the hot gas in a cluster, and therefore the metal abundance excess observed in cluster cores would not be completely erased. This is in contrast with violent mergers of clusters with comparable masses, which completely destroy the central gas structures of the clusters,

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. 2002; Sanders & Fabian 2002; Mazzotta et al. 2003). The temperature jumps seen in Figure 2a may correspond to the ‘cold fronts’ observed in some clusters. Direct observations of the acoustic-gravity waves and the weak shocks evolved from them 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 is $\sim 300{\rm kms}^{-1}$ for $\alpha = 0.3$. With a high spectral resolution detector like the X-ray satellite ASTRO-E2, the turbulence in

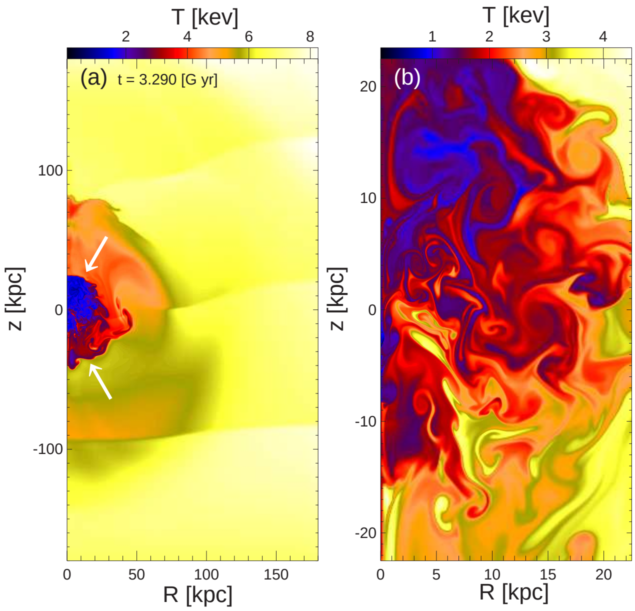

Fig. 2.— A light MHD cylindrical jet. White represents high values and black represents low values.

cluster cores could be detected in the near future (Inogamov & Sunyaev 2003). If turbulence is being developed, the metal lines in the X-ray spectra would have very complicated features owing to the gas motion. 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 $t_{\rm edd} \sim L_{\rm bub}/v_{\rm bub}$, where $L_{\rm bub}$ and $v_{\rm bub}$ are the size and velocity of a bubble, respectively. For the Virgo cluster, for example, the size of the observed bubbles is ~ 10 kpc, and the predicted velocity of a bubble is $\sim 400\ {\rm km\ s^{-1}}$ (Churazov et al. 2001). Thus, the lifetime of the eddies is $t_{\rm edd} \sim 2 \times 10^7$ 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 waves propagated from the outside of the core.

Our model predicts that cooling of a cluster core is more suppressed for larger wave 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 waves 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 simply assumed constant wave 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. These effects should be ultimately studied by fully three-dimensional, cosmological simulations, although the basic mechanism initiating the turbulence would not be different from the one in the two-dimensional case. Second, we did not include the heating by AGNs, thermal conduction, and turbulent dissipation. 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. Third, we fixed the gravitational potential of a cluster. A change in the potential may 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).

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