Turbulence Generation by Substructure Motion in Clusters of Galaxies

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Abstract

Clusters of galaxies form through major merger and/or absorption of smaller groups. In fact, some characteristic structures such as cold fronts, which are likely relevant to moving substructures, are found by Chandra. It is expected that moving substructures generate turbulence in the intracluster medium (ICM). Such turbulence probably plays a crucial role in mixture and transport of gas energy and heavy elements, and particle acceleration. The Astro-E2 satellite, which is planned to be launched in 2005, will detect broadened lines due to turbulent motion. In order to explore the above-mentioned issues, it is important to investigate the generation processes and structure of ICM turbulence. We investigate the ICM dynamical evolution in and around a moving substructure with three-dimensional hydrodynamical simulations. Eddy-like structures develop near the boundary between the substructure and the ambient ICM through Kelvin-Helmholtz instabilities. Because of these structures, characteristic patterns appear in the line-of-sight velocity distribution of the ICM.

Key words: clusters of galaxies, intracluster medium, turbulence

1 Introduction

Clusters of galaxies are the largest virialized objects in the present Universe. According to the standard scenario of structure formation in the Universe, larger objects form more recently. Thus, clusters of galaxies are the virialized objects which form in the most recent epoch in the Universe. In fact, some clusters are forming now, which is evident from the moving substructures

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that are found through X-ray observations (e.g. Markevitch et al., 2000, 2002; Vikhlinin et al., 2001).

A moving substructure causes various characteristic structures in the intracluster medium (ICM). A bow shock and a contact discontinuity will form in front of it. The latter most likely corresponds to a “cold front” which is found by Chandra in a number of clusters (e.g. Markevitch et al., 2000; Vikhlinin et al., 2001). Moving substructures generate turbulence in the ICM through fluid instabilities (Heinz et al., 2003). Turbulence probably plays an important role in cluster evolution. It may have a significant impact on the transport and mixture of heavy elements and on those of thermal energy. Fluid turbulence probably generates magnetic turbulence, which accelerates non-thermal particles and causes various high energy phenomena in the intracluster space (e.g. Ohno et al., 2002; Fujita et al., 2003; Brunetti et al., 2004). The Astro-E2 satellite will detect broadened lines due to turbulent motion (Sunyaev et al., 2003). In order to study the above-mentioned issues, it is crucial to clarify the generation processes and structure of the ICM turbulence.

2 The Simulations

In the present study, we used the Roe TVD scheme to follow the dynamical evolution of the ICM (see Hirsch, 1990). The Roe scheme is a Godunov-type method and is based on a linearized Riemann solver (Roe, 1981). It is relatively simple and good at capturing shocks without any artificial viscosity. Using the MUSCLE approach and a minmod TVD limiter, we obtained second-order accuracy without any numerical oscillations around discontinuities. To avoid negative pressure, we solved the equations for the total energy and entropy conservation simultaneously. This method is often used in astrophysical hydrodynamical simulations where high Mach number flows can occur (Ryu et al., 1993).

Our initial conditions are as follows. We set a subcluster in the center of the simulation box. The subcluster’s gravitational potential is represented by that of a King distribution, whose total mass and core radius are $10^{14}M_\odot$ and 100 kpc, respectively. The subcluster’s radius is 500 kpc. Inside the subcluster, the gas is assumed to be in hydrostatic equilibrium with an isothermal temperature distribution. We set the initial temperature inside the subcluster so that $\beta_{\text{spec}} = 0.8$. We assume that the mass density of the gas is a tenth of that of the DM in the center. Outside the subcluster, the gas pressure is the same as that on the outer boundary of the subcluster and the density is half of the density on that boundary. Only in front of the subcluster we set the initial velocity to twice the sound speed. The size of the simulation box and the number of grid points are $(2 \text{ Mpc})^3$ and $200^3$, respectively. We set constant inflow boundary
Fig. 1. Snapshots of the density distribution on the $z = 0$ surface at $t = 1, 2,$ and 3 Gyr. The substructure's gas in the outer region is stripped off behind the shock because of the ram pressure. A Kelvin-Helmholtz instability developed on the boundary between the substructure and the ambient gas, and prominent eddy-like structures form just behind the substructure.

3 Results

Figure 1 shows snapshots of the density distribution on the $z = 0$ surface at $t = 1, 2,$ and 3 Gyr. Two shocks propagate forward and backward. The shock which propagates backward has left the simulation box before $t = 1$ Gyr. Thus, only the forward shock is seen in figure 1. The substructure's gas in the outer region is stripped off behind the shock because of the ram pressure. In addition, a Kelvin-Helmholtz instability developed on the boundary between the substructure and the ambient gas, and prominent eddy-like structures form just behind the substructure.

Although the eddy-like structures are clearly seen in figure 1, in actual observations we can get only information integrated along the line-of-sight. Therefore, these structures may be less clear in observed quantities. Figure 2 shows snapshots of the X-ray surface distribution seen along the $z$-axis. We assume that the volume emissivity is proportional to $\rho^2 T^{1/2}$, where $\rho$ and $T$ are the gas density and temperature, respectively. Because of contamination of the foreground and background components, the eddy-like structures around the subcluster become less clear.

The Astro-E2 satellite has a high resolution X-ray spectrometer XRS. It will be
Fig. 2. Snapshots of the X-ray surface brightness distribution at $t = 1, 2, \text{and } 3 \text{ Gyr}$. The line-of-sight is just along the $z$-axis. Eddy-like structures around the subcluster become less clear because of contamination of the foreground and background components.

able to detect $\sim 100 \text{ km s}^{-1}$ gas flows through Doppler broadening and/or shift of the emission lines. Because of the symmetry, no line shift is expected in our simulations when the line-of-sight is along the $z$-axis. On the other hand, line broadening is expected because of the bulk flows and turbulent motion. The Line-of-sight velocity dispersion (or standard deviation, equivalently) is a good estimator of line-broadening. Figure 3 shows the emissivity-weighted standard deviation distribution of the line-of-sight velocity component. Around the contact discontinuity in front of the substructure, the root mean square velocity is $\sim 200 \text{ km s}^{-1}$ because of the bulk flows along the convex boundary. Behind the substructure, on the other hand, it becomes $300 \sim 500 \text{ km s}^{-1}$ because of the turbulent motion associated with the eddies.

4 Summary

We investigate the gas motion in and around a moving substructure in a cluster of galaxies using a three dimensional Roe-TVD hydrodynamic code. After the ICM in the outer region of the substructure is stripped off because of the ram pressure, a Kelvin-Helmholtz instability develops on the boundary between the substructure and the ambient ICM. Then, eddy-like structures form there and the cold gas clouds originating from the substructure fly backwards. The line-of-sight velocity dispersion of the ICM becomes large around and in the back of the substructure remnant when we see the system from the direction perpendicular to the substructure motion. The root mean square velocity becomes $300 \sim 500 \text{ km s}^{-1}$, which is large enough to be detected by the Astro-\textit{E2} XRS.
Fig. 3. Standard deviation distribution of the line-of-sight velocity component at 
$t = 1, 2, \text{and } 3 \text{ Gyr}$. Around the contact discontinuity in front of the substructure, 
the root mean square velocity is $\sim 200 \text{ km s}^{-1}$ because of the bulk flows along the 
convex boundary. Behind the substructure, on the other hand, it becomes $300 \sim 500 
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Although in this paper we only showed the results in a rather simple case 
where a subcluster is moving at a constant velocity in a uniform background, 
we are planning to investigate more realistic situations where the ambient 
ICM properties can vary with time. For instance, simulations of a subcluster 
falling into a larger cluster and sloshing near the cluster center will be useful.

In this work, we neglected the magnetic field in the ICM. However, it is possible 
that the magnetic field plays a crucial role to suppress the development of 
Kelvin-Helmholtz instabilities (Asai et al., 2003). On the other hand, the evolution and structure of MHD turbulence contains important information about 
particle acceleration in the ICM. Therefore, high resolution MHD simulations 
will be important as future work.

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