Hydrodynamic Simulations of Merging Galaxy Clusters

– Non-Equilibrium Ionization State and Two-Temperature Structure –

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Abstract

We summarize results of our N-body + hydrodynamic simulations of merging galaxy clusters. In the simulations, assumptions of both the ionization equilibrium and the electron-ion temperature equipartition of the intracluster medium are relaxed, and it is found that the significant non-equilibrium ionization state and the two-temperature structure exist at shock layers in merging galaxy clusters. Line emissions of Fe are significantly altered from that in the ionization equilibrium state at the layers. Understanding such non-equilibrium effects is of crucial importance to constrain physical properties of the intracluster medium such as the temperature and metallicity, and essential to find shock waves in outskirts of the clusters.

Key words: X-rays: galaxies: intergalactic medium — X-rays: galaxies: clusters

1. Introduction

According to the ΛCDM cosmology, shock waves formed through the hierarchical structure formation are ubiquitous and play a key role in heating up the X-ray emitting intracluster medium (ICM). Merging galaxy clusters are sites of the shock waves, thus X-ray diagnoses of merging galaxy clusters give us information for elucidating the heating mechanisms of ICM, acceleration and thermalization of electrons and ions as well as ionization of heavy elements (see Sarazin 2002 for a review). In addition, compression of ICM due to the merger increases the X-ray luminosity at outskirts of galaxy clusters, so that merging galaxy clusters have potential that we detect line emissions from heavy elements and estimate the metallicity in the outskirts, which is an important clue to understand the metal enrichment history of the universe.

The non-equilibrium ionization state and the deviation from thermal equipartition between electrons and ions, or the two-temperature structure, have been theoretically predicted by many authors. For example, the two-temperature structure was studied in numerical simulations of merging galaxy clusters (e.g., Takizawa 1999) or in the structure formation simulations (Yoshida et al. 2003; Rudd, Nagai 2009), while the non-equilibrium ionization state was addressed in cosmological simulations of the warm-hot intergalactic medium (Yoshikawa, Sasaki 2006; Cen, Fang 2006). Recently, Akahori and Yoshikawa (2008) carried out hydrodynamic simulations of merging galaxy clusters incorporating these two effects simultaneously and self-consistently for the first time.

In this contribution, in order to elucidate the ionization state and the temperature structure of ICM in merging galaxy clusters, and to confront them with future X-ray observations, we investigate situations of mergers with various mass ratios and impact parameters as case studies, and situations of two actual merging galaxy clusters, Abell 399/401 and 1E0657-56 (the Bullet cluster).

2. Model and Calculation

We carry out N-body and SPH simulations of two merging galaxy clusters. Initially, ICM in each cluster is on the hydrostatic equilibrium in the NFW dark matter distribution, and the two clusters contact each other at their outer edge with an initial relative velocity. Time evolution of the two-temperature structure is followed in the same way as that by Takizawa (1999), in which Coulomb scattering is only considered for thermal relaxation between electrons and ions. Time evolution of the non-equilibrium ionization state of heavy elements is followed in essentially the same way as that by Yoshikawa and Sasaki (2006), except that reaction rates in the rate equations for all ionic species are calculated using the electron temperature rather than the mean temperature of electrons and ions in order to incorporate the effect of the two-temperature structure. For details, see Akahori and Yoshikawa (2008) and (2009).

3. Results

3.1. Linked Region of Abell 399 and Abell 401

Abell 399 and Abell 401 are in an early stage of the merging. Recently, the metallicity in their linked region is estimated by Suzaku XIS (Fujita et al. 2008). From the simulation of these clusters situation (Akahori, Yoshikawa 2009), we find that there are shock layers with a Mach number of 1.5–2.0 at the edge of the linked region. The electron temperature is 10–20 % lower than the mean temperature of electrons and ions in the layers. The intensity of Fe XXV Kα line emissions, which primary determine the estimation of the metallicity of ICM, is a few % and typically $\sim$ 15% higher than that in the ionization equilibrium in the central part of the linked region and in the shock layers, respectively.

3.2. Systematic Study of Merging Galaxy Clusters

From case studies of merging galaxy clusters (Akahori, Yoshikawa 2009), we find that there are shock layers with a Mach number of 1.5-2.0 in the outskirts of the clusters, and shock layers with a Mach number of 2-4 in front of the dense cores (Fig.1 left). The electron temperature is 10–20 % and 30–50 % lower than the mean temperature of electrons and ions at the shock layers in the outskirts and in the central regions, respectively (Fig.1 center).

Introducing a ratio $R/R_{\rm eq}$ as a plausible tracer of the deviation from the ionization equilibrium state, where $R = I(6.6 - 6.7\ {\rm keV})/I(6.9 - 7.0\ {\rm keV})$ corresponds to the ratio between Fe XXV and Fe XXVI Kα intensities, and $R_{\rm eq}$ is the ratio under the assumption of the ionization equilibrium and thermal equipartition, we find that $R/R_{\rm eq}$ is slightly below unity at the shocks in the outskirts, and significantly exceeds unity at the shocks in the central regions (Fig.1 right). These results are explained by the fact that Fe XXV is under- and overpopulated compared with the ionization equilibrium state at the shocks in the outskirts and in the central regions, respectively, because the ionization to Fe XXV from lower and the ionization of Fe XXV to the higher ionization levels are not quick enough to catch up with the ionization equilibrium state, respectively.

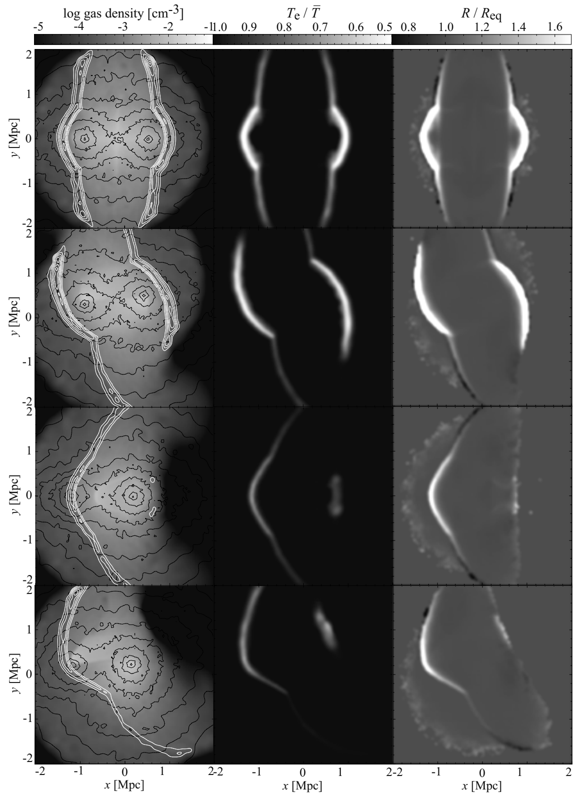

Fig. 1. Case studies of mergers with different mass ratio and different impact parameter, 1:1 head on, 1:1 offset, 4:1 head on, and 4:1 offset (from the top to the bottom) at a time of $t = 1.0$ Gyr, where $t = 0$ Gyr corresponds to the time of the closest approach between the centers of the dark matter halos, and the impact parameter of $b = 0.81$ Mpc is adopted for the offset runs. (left) ICM density maps on a collision plane of the two clusters. Distributions of dark matter are also overlaid with black contours. White contours indicate the Mach number distribution of ICM from 1.5 to 4.0 by a difference of 0.5. (center) The ratio of the electron temperature relative to the mean temperature of electrons and ions on the collision plane. (right) $R/R_{\rm eq}$ maps.

3.3. The Bullet Cluster 1E0657-56

1E0657-56 is in a late stage of the merging. There is a shock front with a Mach number of $\sim$ 3 (Markevitch 2006). From the simulation of the 1E0657-56 situation, we find that $R/R_{\rm eq}$ is $\sim$ 1.1 at the shock layer. If the two-temperature structure exists at the shock layers, the electron temperature around the shock layers is $\sim$ 40 % lower than the mean temperature of electrons and ions, and $R/R_{\rm eq}$ is significantly exceeds unity, and is $\sim$ 1.3.

4. Conclusion

The non-equilibrium ionization state and the two-temperature structure are one of the certain evidences and indicators of shock waves in merging galaxy clusters, and could be detected by future X-ray spectroscopy (Astro-H and IXO).

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