From intracluster medium dynamics to particle acceleration

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English Summary

Galaxy clusters are nodes of the Cosmic Web, and are the largest virialized *halos* in the Universe, with masses of about $10^{14} - 10^{15}\ M_{\odot}$. Beside the five sixths of the mass content that is in the form of dark matter, the intracluster medium (ICM) permeating the vast space between the member galaxies amounts for most of the remaining one sixth baryonic content. The gaseous cluster atmosphere is extremely tenuous and hot. The number density of the ICM is $< 10^{-2}$ cm^{-3}, which is much lower than achieved in the best vacuum lab on Earth. The temperature can reach 10^{8} K, meaning that heavy elements such as Fe are ionized to H- and He-like ions. Meanwhile, the intracluster space is turbulent, and cluster mergers play a key role in stimulating the gas motions. These gas motions lead to large scale density discontinuities in the forms of cold fronts and shock waves, and thermodynamic fluctuations due to turbulent motions.

At radio frequencies, galaxy clusters, especially merging clusters have been found to host extended synchrotron sources, which have scales up to a Mpc and are characterized by steep spectra. Based on radio properties such as morphology and polarization, these sources are classified as radio relics and radio halos. Investigating particle acceleration mechanisms in the ICM is the key to unveil the origin of these extended cluster radio sources. The two widely accepted acceleration mechanisms for radio relics and radio halos are shock acceleration and turbulent acceleration, respectively. Both of these scenarios are due to ICM motions. Therefore, X-ray observations of the ICM are important for quantifying shock wave and turbulence properties to test the acceleration models. The properties of shock waves can be quantified based on Rankine-Hugoniot condition by measuring the upstream and downstream thermodynamic properties.

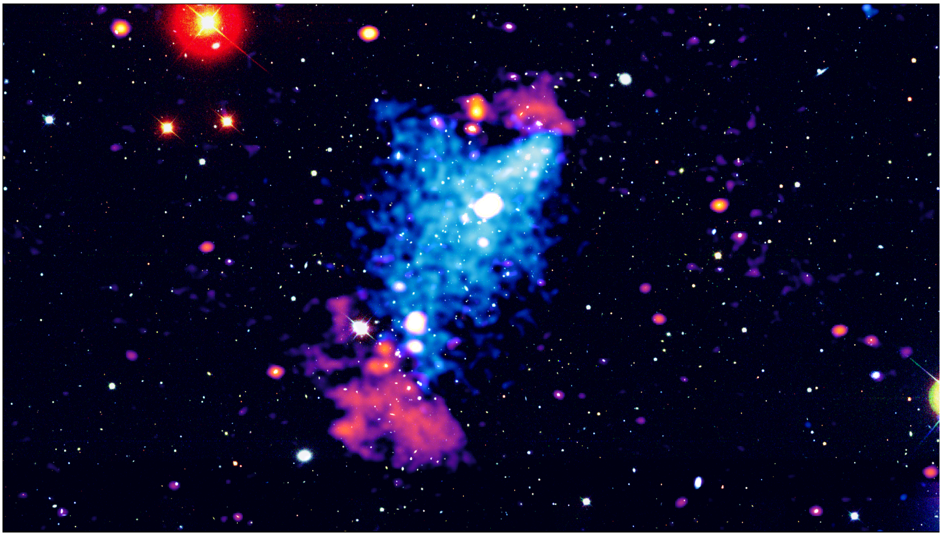

Figure B.1: Merging galaxy cluster ZwCl 2341+0000, which hosts two radio relics on the opposite sides.

The turbulent velocity dispersion can be estimated by measuring the density fluctuation amplitude or in the near future by line shifts and widths of high resolution spectra.

This thesis

This thesis focuses on X-ray observations of galaxy clusters. The main goal is to establish and further explore and the connections between X-ray and radio phenomena.

1. The connection between shocks and radio relics

   In **Chapters 2** and **3**, we analyzed deep X-ray observations of two merging clusters, Abell 3411-3412 and ZwCl 2341+0000. The deep observations reveal the ICM thermodynamic structure around radio relics and illustrate that both shock waves and cold fronts could spatially overlap with radio relic emission. Among them, the projected positions of shock waves are close to the outer edges of radio relics, which supports the shock acceleration scenario.

Comparing the results between the deep and previously published shallow observations, one crucial message is that shock waves could be confused with cold fronts based on the similar features of surface brightness jumps. X-ray spectral analysis is necessary to confirm the shock wave nature of a surface brightness jump based on its thermodynamic properties that are distinct from those of cold fronts.

2. The connection between shocks and radio halo edges

   Chapter 4 reports two X-ray surface brightness jumps at the location of the radio halo edge in galaxy cluster ClG 0217+70. These are new candidates of shock wave - radio halo association, if their shock wave nature is confirmed by the upcoming deep X-ray observations. This discovery as well as a handful of previously reported cases suggest that shock waves may also play a role in shaping radio halos.

3. The connection between turbulence strength and radio halo power

   In **Chapter 5**, we investigate the relation between radio halo power and properties of ICM turbulence using the sample in the second data release of the LOFAR Two-metre Sky Survey. The Mach number of turbulence is estimated by calculating the power spectrum of X-ray surface brightness fluctuations, which is found to be correlated with the cluster dynamic state. Moreover, by calculating the turbulent dissipation flux, we find it is correlated with radio halo power with a regression slope close to unity, suggesting an underlying connection between particle acceleration and the ICM turbulent motions.

In addition to constraining the properties of the largest particle accelerators in the Universe, this thesis addresses diverse topics on X-ray observations of galaxy clusters. In **Chapter 2** and **5**, we develop methods for modeling the focused and unfocused non X-ray background for the *XMM-Newton* EPIC imaging spectrometer, which reduce the systematic uncertainty for data analysis in background dominated regions. In **Chapter 3**, we discover a unique cone-like core remnant in the merging cluster ZwCl 2341+0000, which implies a short transition stage of the core remnant in a head-on merger. **Chapter 4** illustrates the power of X-ray spectroscopy on measuring the redshift of a galaxy cluster behind the Galactic plane, whose optical data suffers from systematic uncertainties due to extinction.