X-ray spectroscopy of merging galaxy clusters

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Summary

Galaxy clusters are the largest virialized objects in the Universe, which contain between a hundred to a thousand of galaxies. These galaxies are surrounded by hot ionized plasma, known as intracluster medium (ICM) and it is observed in X-rays. The galaxies constitute only $\sim$5% of the total mass, while the ICM includes around $\sim$15%. The rest of the mass, $\sim$80%, is dominated by dark matter. Galaxy clusters can be observed using different wavelengths, although the most relevant for this work are optical, X-ray and radio observations (see Fig. A). Optical observations reveal the individual galaxies and their overdensity at a similar redshift. In X-rays the spectral properties (for example, temperature, density or abundance) of the ICM can be derived. Moreover, radio observations show discrete and extended radio sources, trace the cosmic rays and the energetic particles acceleration. Galaxy clusters are usually classified in different groups based on their dynamical state: relaxed or cool-core (CC) clusters, disturbed or non-cool-core (NCC) clusters and extremely disturbed or merging galaxy clusters.

Galaxy clusters grow hierarchically via accretion and merging of less massive groups or subclusters. Cluster mergers are the most energetic events in the Universe since the Big Bang. Turbulence, shocks and cold fronts arise in the hot ICM as a result of the strong merging activity. Shocks are large scale structures that propagate from the cluster center to the periphery, where they are usually found. They can be detected by temperature and density discontinuities in the ICM via spectral analysis and detection of X-ray surface brightness edges, respectively. Shocks ($\mathcal{M} \leq$ 3–5) are thought to (re)accelerate electrons, in the presence of an amplified magnetic field, via first-order Fermi diffusive shock acceleration (DSA). Nowadays alternative acceleration mechanisms have been also proposed such as the re-acceleration of the pre-existing cosmic ray electrons, among others. These relativistic particles may produce non-thermal synchrotron emission in the form of elongated, polarized and steep-spectrum structures known as radio relics. In some merging clusters this radio emission appears associated to an X-ray counterpart (X-ray shocks).

The ICM of galaxy clusters is rich in metals, which originate mainly from core-collapse supernovae (SNcc), type Ia supernovae (SNIa) and low-mass stars on the asymptotic giant branch (AGB). SNcc release primary light metals (O, Ne, Mg, Si and S), while heavier metals (such as Ar, Ca, Mn, Fe, and Ni) are expelled by SNIa. The main contribution of C and N

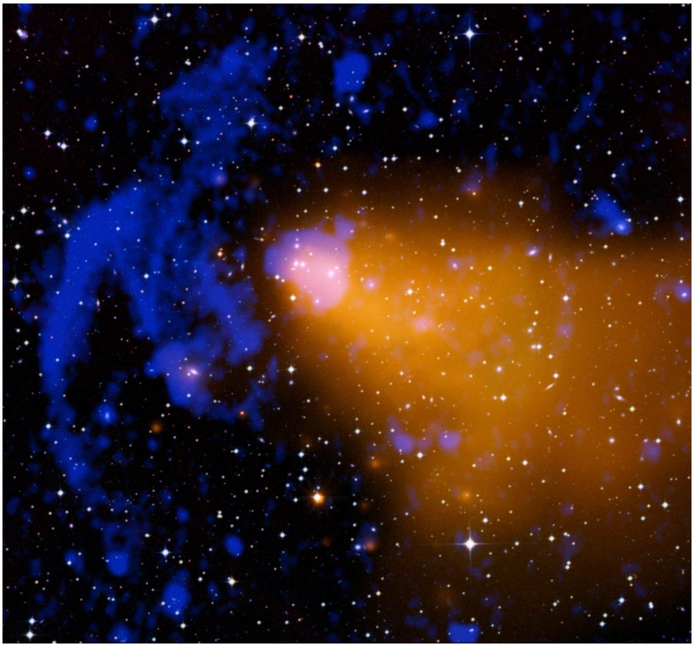

Figure A: Composite image (optical, X-ray in orange and radio in blue) of the galaxy cluster Abell 3376. Credit: X-ray (NASA/CXC/SAO/A. Vikhlinin; ROSAT), Optical (DSS), Radio (NSF/NRAO/VLA/IUCAA/J. Bagchi).

come from AGB. Once the metals are ejected to the ICM, they are later transported, mixed, and redistributed. During the last years, the Fe abundance distribution of CC and NCC clusters has been widely analyzed. However, few studies have been done centered on the merging galaxy clusters. A better understanding of the metals distribution along the merging axis can reveal the chemical evolution and history of these large scale structures. The Fe radial distribution of CC clusters present a high central metal-rich peak compared with NCC clusters, which flattens at large radii towards a uniform distribution around $\sim$0.2–0.3 $Z_\odot$. This same behavior is observed in NCC clusters, which suggest an early enrichment scenario of the ICM ($z \sim$ 2–3).

X-ray spectroscopy represents a useful tool to determine all these thermodynamical and chemical properties of the ICM mentioned above. For this reason updated spectral plasma codes with high accuracy are completely needed to model and fit X-ray spectra of galaxy clusters. SPEX is one of these spectral modeling, fitting and analysis software packages. SPEX has been recently updated to v3.0 driven by the high-resolution observation requirements expected by the *Hitomi* and future missions, *XRISM* and *Athena*. The major improvements have been focused on the update of the radiative processes such as radiative recombination, collisional ionization, charge exchange or photoionization and the incorporation of a large number of emission and transition lines.

This thesis focuses on the X-ray analysis of merging galaxy clusters and the plasma code development for future high-resolution X-ray spectroscopic observations. This work is devoted to a better understanding of two concrete aspect of these merging clusters: one, the correlation between the thermal (X-ray) and the non-thermal (radio) components, and two, their metal enrichment history. The first issue can reveal the physical association between the X-ray and radio components. The second one can seed light on the dynamical history of the mergers and their role in the metal enrichment of the clusters.

In Chapter 2, we show the X-ray study of the merging galaxy cluster Abell 3376 observed with *Suzaku*. We study the spatial distribution of the thermal component of the ICM including the cluster outskirts. For this purpose, we obtain the temperature distribution in four different radial directions (west, east, north and south). We compare these distributions with the universal profile of relaxed clusters and we find a deviation for all the directions except for the south, suggesting the possible presence of shocks. However, we only find evidence of two shocks at west and east. One is associated to the western radio relic with $\mathcal{M} \sim 2.8$ and the other to the eastern 'notch' with a $\mathcal{M} \sim 1.5$. We detect as well a cold front at the east of the X-ray emission peak. The Mach number of the eastern shock is consistent with previous radio observations, while the western radio relic present a slightly lower one, probably due to radio ageing effects. Finally we investigate the merger scenario, which suggests a merger close to the plane of the sky with a dynamical age of $\sim$0.6 Gyr after core passage.

In Chapter 3, we investigate the thermodynamical properties of the hot plasma across the merging galaxy cluster Abell 3365 using *XMM-Newton* observations. For this purpose, first, we search for X-ray surface brightness and temperature discontinuities at the clusters outskirts and central ICM edges. Second, we obtain the temperature, Fe abundance and pseudo-entropy distributions along the merging axis in the central bright region. We find two strong shocks ($\mathcal{M} > 3$) associated to the eastern radio relic and western candidate relic and one cold front at the west of the X-ray emission peak. The shock acceleration efficiency at the eastern relic is consistent with the DSA mechanism, suggesting that this is a favorable scenario for shocks with $\mathcal{M} > 3$. The abundance distribution presents signatures of two peaks with a value of $\sim$0.6 $Z_{\odot}$. One corresponds to the location of the main subcluster and the other one is displaced from the X-ray emission peak towards the cold front. We also find a low entropy minimum, which suggests that the progenitor cool-core can partially or totally survived to the merging activity.

In Chapter 4, we present an X-ray spectral analysis of six merging galaxy clusters (CIZA J2242.8+5301, 1RXS J0603.3+4214, Abell 3376, Abell 3667, Abell 665 and Abell 2256) observed with *XMM-Newton*. We obtain the temperature, Fe abundance and pseudo-entropy distributions along the merging axis up to r_{500}. We derive the averaged Fe profile, which presents a moderate central peak, lower than relaxed clusters, followed by a smooth flattening up to a uniform value of $\sim$0.2–0.3 $Z_{\odot}$ at large radii. Moreover, the pseudo-entropy distributions suggest that in some cases the relative low entropy core can survive to major mergers. We also study the correlation between Fe abundance and pseudo-entropy. We find a mild correlation in the central regions, probably due to the merging activity and the spread out of the metals. However, there is no evidence of correlation at large radii, in the cluster outskirts. This result together with the abundance uniformity seems to suggest an additional evidence in favor of the pre-enrichment scenario.

Lastly, in Chapter 5, we update with 45 new data sets the single ionization cross sections for ions from H to Zn, taking into account the new theoretical calculations and laboratory measurements. The cross sections of the rest of the ions with no data sets, are interpolated or extrapolated. We are able to obtain not only the total, but all the inner shells cross sections for the first time. These cross sections include two different radiative processes: the Direct Ionization (DI) and Excitation-Autoionization (EA). We model and fit the DI and EA processes using an extension of Younger's and Mewe's equations to obtain the DI and EA coefficients. We derive the subshell ionization rate coefficients applying the integral to a Maxwellian velocity distribution of these equations. Finally, we incorporate the DI, EA and ionization rate coefficients to the new version of SPEX v3.0.