Background

Abstract: Galaxy clusters grow through colliding and merging with other clusters and groups of galaxies. Minor mergers are relatively common and create sloshing cold fronts in the ICM of the host cluster, which are seen as sharp discontinuities in X-ray surface brightness which persist for extended times. We present preliminary results from a suite of *triple* cluster mergers exploring whether subsequent minor mergers can disrupt sloshing cold fronts and whether this more complex merger history can be determined from sloshing patterns.

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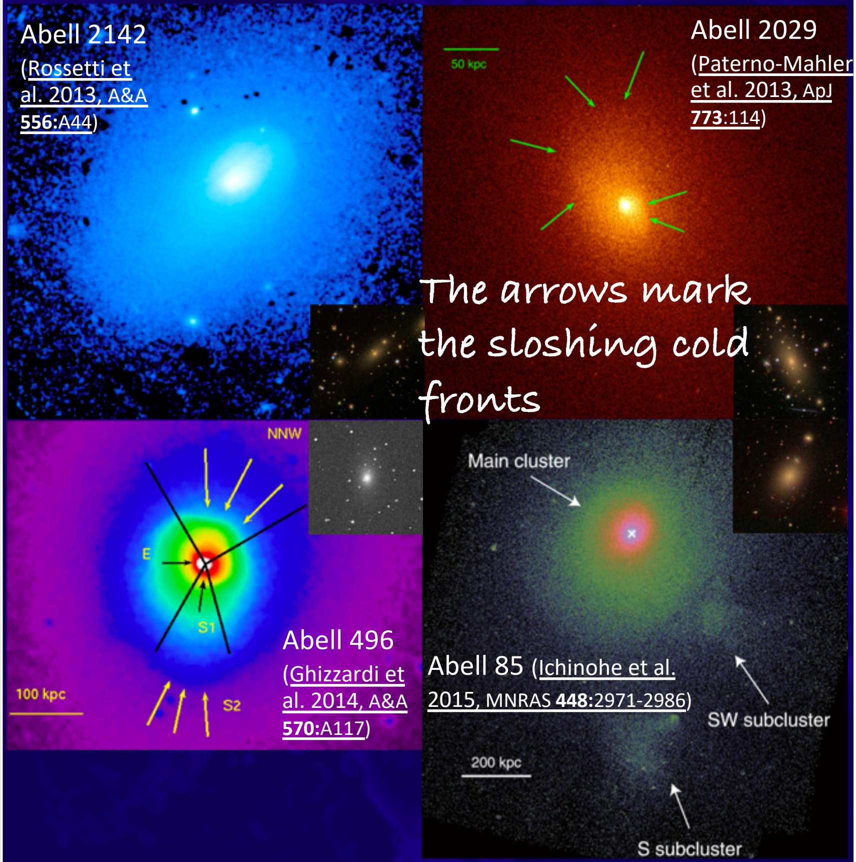
Introduction

Galaxy clusters are the largest objects in the Universe that have had time to settle into a stable configuration. They contain anywhere from 50 galaxies to thousands, weighing, in total, around 10^{14}-10^{15} Solar masses. They grow, according to the current standard model of cosmology, by accreting smaller groups of galaxies and by merging with one another due to their mutual gravity. Cluster mergers are the most energetic events in the Universe since the Big Bang and drive shocks through the Intra-cluster medium (ICM), the hot plasma that pervades the whole cluster, compressing and heating it, leading to multiple interesting observable effects. Mergers can broadly be categorized in two ways: major (two clusters of roughly equal mass) or minor (the primary cluster is roughly four to ten times more massive than the secondary). Using hydrodynamical simulations of galaxy cluster mergers, we can understand the evolutionary stages of such mergers.

Examples of sloshing



Abell 2142 (Rossetti et al. 2013, A&A **556**:A44)

Abell 2029 (Paterno-Mahler et al. 2013, ApJ **773**:114)

Abell 496 (Ghizzardi et al. 2014, A&A **570**:A117)

Abell 85 (Ichinohe et al. 2015, MNRAS **448**:2971-2986)

The arrows mark the sloshing cold fronts

Figure 1: X-ray images (false-colour, the centres are brightest) of galaxy clusters showing cold fronts in their ICM. The insert shows the optical counterpart of the cluster centre.

Cold Fronts & Sloshing

Both cold fronts and shocks appear in X-ray surface brightness as sharp edges. In contrast to a shock, a cold front is colder on the denser side of the discontinuity and the ICM pressure is continuous across the front. The first example was discovered in Abell 2142 (Markevitch et al. 2001, ApJ **541**:542; Vikhlinin et al. 2001, ApJ **551**:160). Sloshing cold fronts wrap around the cluster core (see Figure 1); they arise when an off-axis minor merger perturbs the core of the primary cluster, imparting angular momentum and causing the primary cluster's ICM to 'slosh' about the gravitational potential, producing arc-like edges at small cluster-centric radii (≲100kpc) (Tittley & Henriksen 2005, ApJ **618**:227; Ascasibar & Markevitch 2006, ApJ, **650**:102–127; Owers, Nulsen & Couch 2011, ApJ **741**:122-144) The sloshing fronts persist for extended times (>1Gyr) (Roediger 2012, MNRAS **420**:3632–3648) and are expected to be common in massive clusters because minor mergers are common (Hallman et al. 2010, MNRAS **725**:1053–1068).

Simulations

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FLASH & Initial Conditions

We run 12 simulations (two presented here) using the FLASH hydrodynamics+N-body code (v4.3) (Fryxell 2000, ApJ **131**:273-334). We model the ICM gas as a beta profile with dark matter (DM) particles overlaid in a Hernquist profile. The main cluster (in hydrostatic equilibrium) has a mass of 5.0×10^{14}M$_{\text{Sun}}$ (with 5×10^6 DM particles) and the accreted clusters each have a mass of 5.0×10^{13}M$_{\text{Sun}}$ (with 5×10^5 DM particles).

The simulations are run with the main cluster at rest, with the secondary and tertiary clusters travelling at velocities and impact parameters in accordance with the findings of Vitvitska et al. 2002 (ApJ **581**:799). The mass ratio between the clusters is 1:10 (chosen based on the findings of ZuHone 2011 (ApJ **728**:54-78) in which this mass ratio is shown to produce clear sloshing fronts, albeit with gasless secondary clusters). The two simulations chosen for preliminary analysis here share a common trajectory for the first infalling cluster, but differ in the trajectory of the second infaller. The state of the simulations at initialisation is shown in figure 2. The sloshing fronts established in both simulations by the first merger are seen in figure 3.

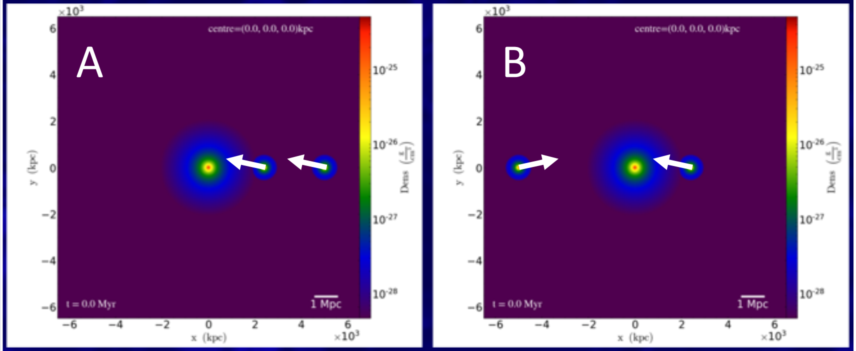

Figure 2: Density slice plot of the initial state of simulations A and B with exaggerated velocity quivers

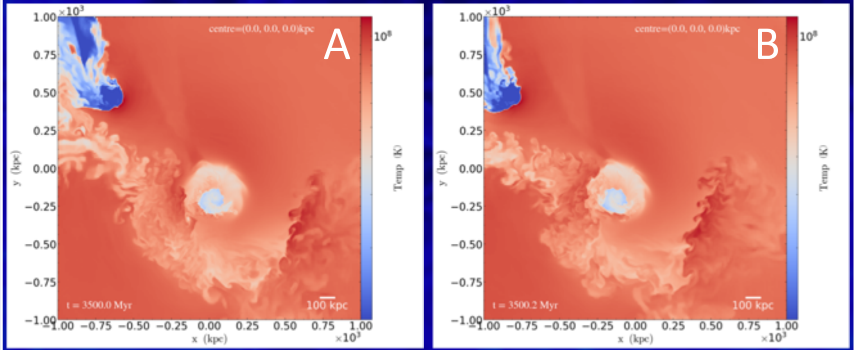

Figure 3: Temperature slices in the merger (x,y) plane. Sloshing cold fronts can be seen in the core of the host cluster. The cool object approaching from the north-west is the first infaller coming back for its second pericentric passage.

Aims

Minor mergers are known to create sloshing cold fronts in their host cluster, but these are subtle features which are due to only subsonic motions of the ICM. A subsequent minor merger could potentially destroy or disrupt the sloshing pattern created by the previous merger. As minor mergers are common, it is important to understand the resilience of sloshing cold fronts to correctly derive a cluster's merger history based on their properties.

We have therefore performed a suite of simulations exploring precisely this. The suite consists of 12 simulations, each representing a different trajectory of the tertiary cluster. The first merger initiates the sloshing in the primary cluster and is common to all simulations in the suite. We then track the effect a second minor merger has on these sloshing fronts.

Can sloshing fronts persist in spite of subsequent mergers, and if so, under which merger conditions?

Can we still deduce the merger history from the size and orientation of the sloshing pattern?

Can cold fronts at larger radii caused by the multiple merger help to disentangle merger history?

Results

Abstract: Galaxy clusters grow through colliding and merging with other clusters and groups of galaxies. Minor mergers are relatively common and create sloshing cold fronts in the ICM of the host cluster, which are seen as sharp discontinuities in X-ray surface brightness which persist for extended times. We present preliminary results from a suite of *triple* cluster mergers exploring whether subsequent minor mergers can disrupt sloshing cold fronts and whether this more complex merger history can be determined from sloshing patterns.

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Simulation A

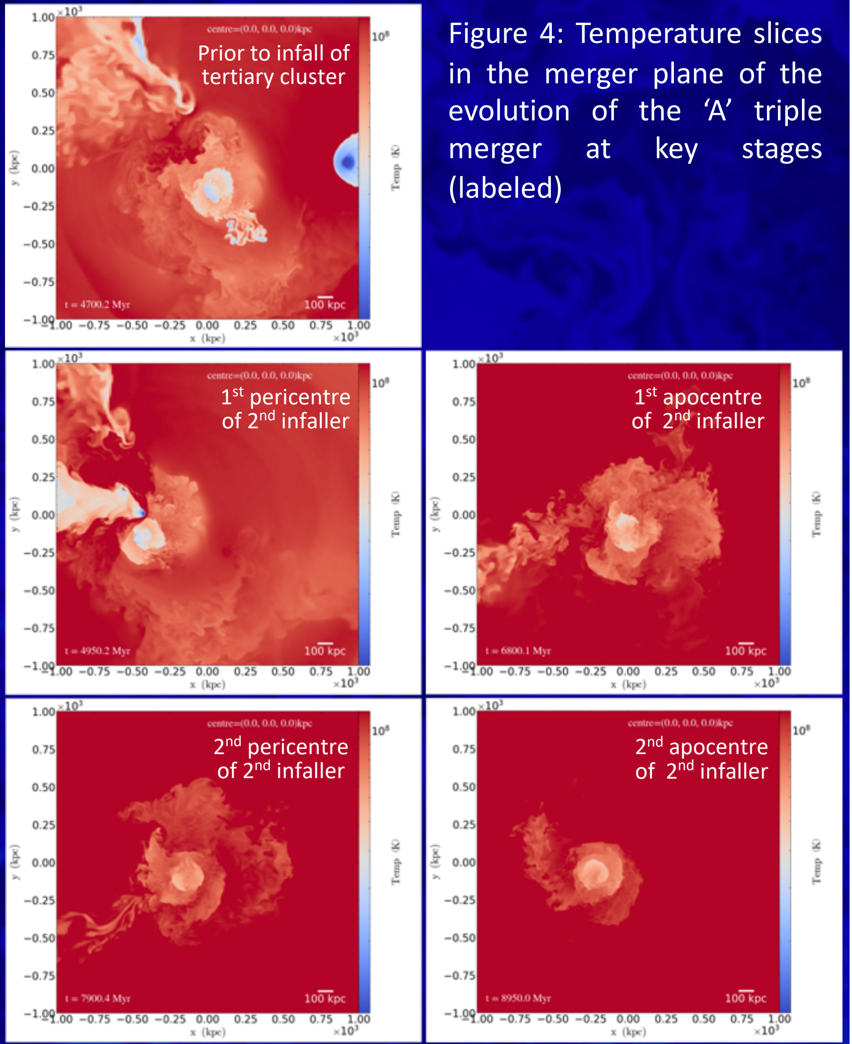

Figure 4: Temperature slices in the merger plane of the evolution of the 'A' triple merger at key stages (labeled)

Merger Evolution

Presented here are snapshots of key stages in the evolution of the triple merger scenarios introduced in the previous slide. The images are slices of the temperature in the x-y plane (the plane the merger takes place in). The colour-scale ranges from 1.16×10^7-1.16×10^8K with red being hotter and blue colder. Sloshing fronts can be seen at 4.7Gyr in the first panel of each figure (4 and 5) prior to the tertiary cluster's first impact. We then see the sloshing fronts become disturbed throughout the first infall of the tertiary cluster (~4.9-6.8Gyr) before reappearing at first apocentre of the tertiary cluster and remaining present thereafter. At the end of the simulations (8.95Gyr) both systems exhibit clear cold fronts.

Simulation B

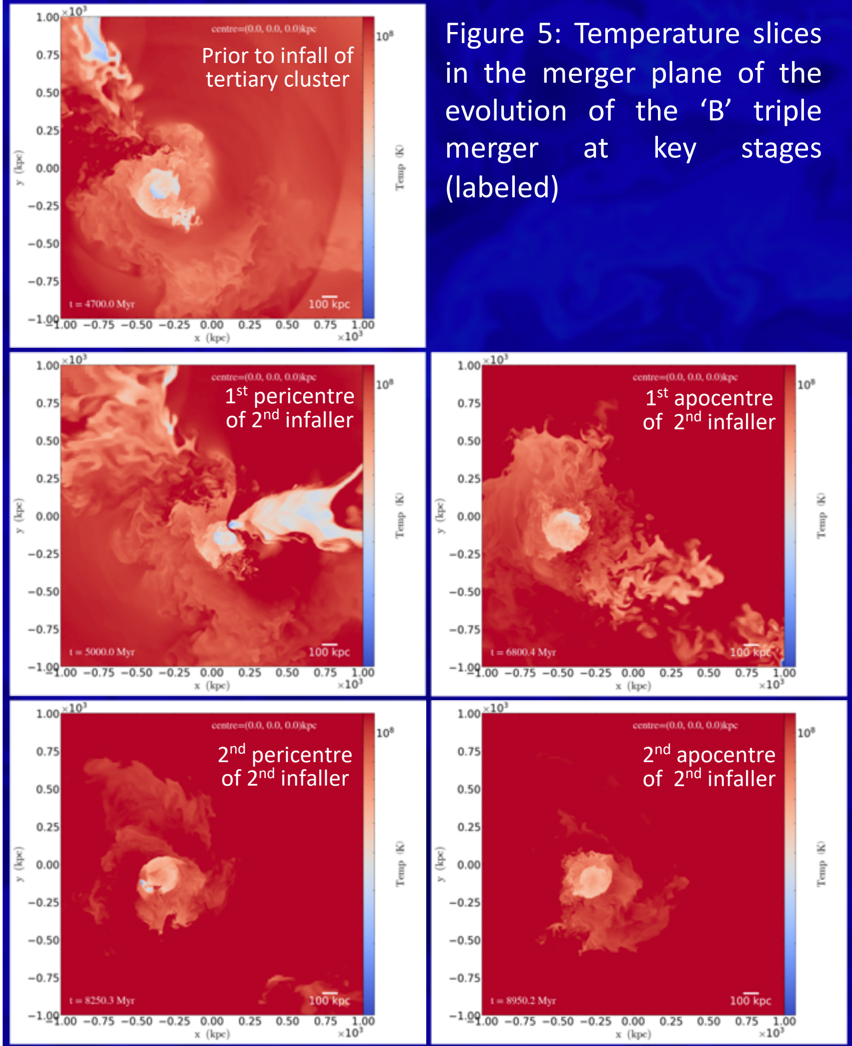

Figure 5: Temperature slices in the merger plane of the evolution of the 'B' triple merger at key stages (labeled)

Summary

Abstract: Galaxy clusters grow through colliding and merging with other clusters and groups of galaxies. Minor mergers are relatively common and create sloshing cold fronts in the ICM of the host cluster, which are seen as sharp discontinuities in X-ray surface brightness which persist for extended times. We present preliminary results from a suite of *triple* cluster mergers exploring whether subsequent minor mergers can disrupt sloshing cold fronts and whether this more complex merger history can be determined from sloshing patterns.

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First Results

- Sloshing cold fronts form around the core of the primary cluster, as expected, due to the first off-axis minor (1:10) merger.
- The infall of the tertiary cluster disrupts the established sloshing fronts until it has reached its first apocentre.
- Sloshing fronts re-emerge after the 1st apocentre of the 2nd infalling cluster and remain until the end of the simulation, suggesting that once sloshing cold fronts have been established, they are difficult to disrupt.
- The second infaller, in both clusters, retains most of its gas as it passes the primary's core, as is the case for the first infaller.

Future Work

- Expand the analysis to include all the different simulations – determine whether the key evolutionary stages of each merger yield similar features.
- Determine whether cold fronts at larger cluster-centric radii can be used in any way to distinguish single from multi-mergers
- Consider projections effects, for example:

i. does the angle from which the merger is viewed have an effect on whether sloshing fronts can be used to disentangle the merger history;

ii. do certain observables (e.g. temperature) provide a key insight into merger history via sloshing;

iii. can certain viewing angles allow an infalling cluster to 'hide' in some configurations.

The Team

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