The role of gas and dark matter in the dissociative collision of galaxy cluster Abell 2034

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Abstract: Collisions between galaxy clusters are a frequent scenario in the hierarchical model of structures. Dissociative collisions provide an extreme environment of interaction between clusters of galaxies, where the properties of dark matter (DM) in relation to baryonic matter become evident. Investigating dissociative scenarios allows a deeper understanding of the behavior and dynamics of baryonic and non-baryonic matter in this context of collision. Abell 2034 ($z = 0.114$) is a bimodal system composed of a north and a south substructure, it has dissociative features observed in X-rays and gravitational lensing. Using N-body hydrodynamic simulations, we present a theoretical study based on the dissociative collision of A2034, aiming to explore the effect that different relative concentrations between the clusters generate on the dynamics of the system. We investigated the relationship of the central density ratios with different levels of dissociation, where we analyzed nine models with different concentrations of the two components: intracluster gas and DM halo for each substructure. We found different degrees of dissociation that were quantified by the relative distance between the X-ray emission peak and the dark matter peaks. We found that the ratio of the gas central densities is more decisive than the ratio of dark matter central densities, in determining the level of dissociation for the parameters of this collision.

1 Introduction

Dissociative systems are a peculiarity of collisions between galaxy clusters, and are known in the literature since 2006 with the Bullet Cluster (Clowe et al., 2006). Abell 2034 (A2034) is a cluster at local Universe ($z = 0.114$) that has dissociative features. The A2034 is composed of two substructures: A2034N and A2034S. The main points about recent developments of the A2034 in the literature are:

- The distance between the X-ray emission peak and the south dark matter peak is around 348 kpc, where the distance between both total mass peaks is ∼720 kpc (Monteiro-Oliveira et al., 2018). Implying in a clearly dissociative system, with gas approximately in the middle of two DM peaks.
- This merger system has been observed by X-ray satellites since *ROSAT* (David et al., 1999), and more recently by XMM-*Newton* (Okabe & Umetsu, 2008) and *Chandra* (Kempner et al., 2003; Owers et al., 2014).
- More recently mass reconstruction are performed by weak gravitational lensing method in 2018 by Monteiro-Oliveira et al. (2018).

Numerical simulations were developed motivated by the analysis of X-rays and gravitational lensing, leading to a proposed scenario for this collision, where we observed the system at 0.26 Gyr after the central passage (Moura et al., 2021). From this numerical scenario, we carry out a theoretical exploration of the effect that different gas and DM concentrations cause in the dissociation of the A2034 merger system.

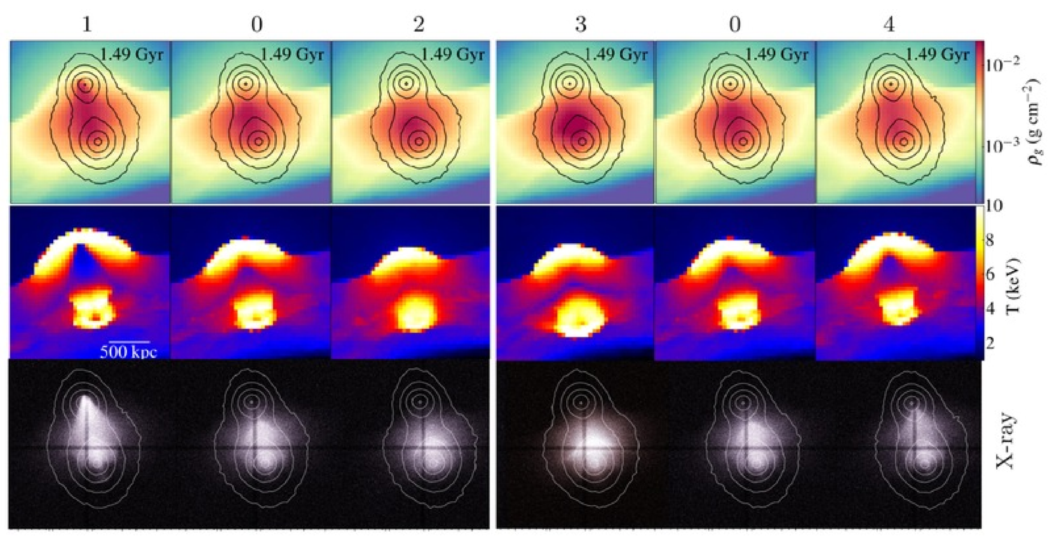

Figure 1. Gas scale length variations, for north (200, 300 and 400 kpc) and south (300, 400 and 500 kpc) substructures. The first row shows gas density maps with contours representing total mass. The second row shows projected temperature maps for each model. The third row shows X-rays mocks from counts/pixel and contour curves of the total mass.

2 Simulation setup

We aim to investigate the dissociative collision of Abell 2034 using N-body hydrodynamic simulations. To simulate this merger context, we set up two spherical galaxy clusters. The code employed and details about the simulation are:

- We adopt the GADGET-2 code (Springel, 2005), which uses smoothed particle hydrodynamic (SPH);
- The initial conditions are composed of 10^6 gas particles and 10^6 DM particles for each cluster;
- The south and north substructure were created with masses similar to the virial masses $M_{200}^{\rm S} = 2.35 \times 10^{14}\,{\rm M}_\odot$ and $M_{200}^{\rm N} = 1.08 \times 10^{14}\,{\rm M}_\odot$ (Monteiro-Oliveira et al., 2018). The initial M200 conditions have 85% of dark matter mass and 15% of gas mass. Galaxies, star formation and cosmological expansion are not considered;
- To perform the simulation, we assume a Hernquist (1990) profile for DM halo density, and a Dehnen (1993) profile for gas density distribution, respectively:

$$\rho_{\rm h}(r) = \frac{M_{\rm dm}}{2\pi}\frac{a_{\rm dm}}{(r+a_{\rm dm})^3}, \text{ and } \rho_{\rm g}(r) = \frac{3M_{\rm gas}}{4\pi}\frac{a_{\rm gas}}{(r+a_{\rm gas})^4}, \quad (1)$$

where $M_{\rm dm}$ and $M_{\rm gas}$ represent total DM and gas mass, and consequently $a_{\rm dm}$ and $a_{\rm gas}$ is the scale length for DM and gas.

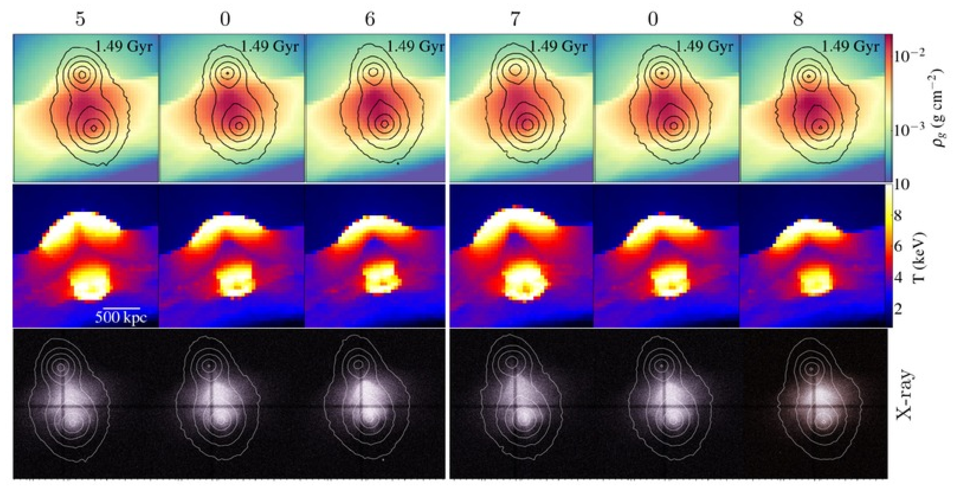

Figure 2. DM halo scale length variations for north and south substructure, same to the Fig.1

3 Results

The present summarized discussion is based on a theoretical exploration detailed in Moura et al. (2021), where it was explored the relationship between the initial central densities of gas and dark matter with different dissociation levels based on A2034 bullet-like system. The different collision models with different gas and DM concentrations were executed keeping the other simulation parameters fixed in the best model. Therefore is possible to investigate the effects that different concentrations cause on the collision, uniquely. There are more and less concentrated models, small-scale lengths are defined as being more concentrated, in contrast, large scale lengths are defined as being less concentrated models in inner regions in relation to the model default.

3.1 A2034 models

We vary the scale length of the gas and DM halo for the south and north substructures, around the default model '0' (best model of simulation). The default model scale length is defined according to with the expected concentration c, given the mass and redshift of each substructure (Duffy et al., 2008), being them: $a_{\rm g} = a_{\rm h} = 300$ kpc for the northern substructure and $a_{\rm g} = a_{\rm h} = 400$ kpc for the southern substructure. Given the both substructures scale length of model 0, we consider a smaller and a larger scale length around this value for gas and DM, for A2034N and A2034S. This variation produces nine models, which can be seen in Fig. 1 and 2. The models configuration are:

- Models 1, 0 and 2 the north gas scale length is varied in 200, 300 and 400 kpc, keeping the southern cluster and halo scale length fixed (left panel of Fig. 1);
- Models 3, 0 and 4 the gas scale length for the southern subcluster was varied in the same way by 300, 400 and 500 kpc (right panel of Fig. 1);
- Models 5, 0 and 6 the DM scale length for the nortern subcluster was varied (200, 300 and 400 kpc), keeping other parameters fixed (left panel of Fig. 2), and
- Models 7, 0 and 8 the DM scale length for the southern subcluster was varied in 300, 400 and 500 kpc (right panel of Fig. 2).

Therefore, each model represents a different collision of A2034 observed at 0.26 Gyr after the core passage. Fig. 1 and Fig. 2 shows the effect that different gas and DM concentrations cause in the behaviour of the gas, respectively. Each column has a scale length, representing the gas and DM more or less concentrated, for the northern and southern substructure in the left and right panel, of each figure (left for the northern and right for the southern cluster). Visually, we can conclude that both the different gas and DM scale lengths cause different effects on the gas, mainly in morphology, causing different dissociative degrees.

3.2 DM and gas separation

To quantify the offset for the models of A2034 with different concentrations, we measured the ratio of initial central densities of gas and DM for each model, considering N/S. Thus, with a radius of 50 kpc around the centre of each substructure with different scale lengths, we have obtained different fractions of pair of concentrations. In this context, Fig. 3 quantifies the offset of gas emission in relation to the south dark matter peak in each model, depending on the initial central densities of the gas (left) and DM (right). The correlation is shown for four simulation times after the central passage: two moments before and one after the best time ($t = 1.49$ Gyr) (Moura et al., 2021). The X-ray centroid is defined how the average position of gas particles weighted by X-ray emission. The summary of results are:

- Visually (Fig. 1) and quantitatively (left of Fig. 3) it is possible to notice that the displacement of the gas is strongly related to the central gas density ratios. Showing a regular pattern as a function of gas concentration.
- For DM concentration variations in the right-hand panel of Fig. 3, the dependence between the mass peaks distances is much less pronounced given the different concentrations for two subclusters. This result also is verified visually by the Fig. 2, in contrast with the Fig. 1.
- The variations for the DM concentration indicate that the relationship between DM scale length and the gas displacement is not as important as the gas scale length for the dissociative offset, promoting small chances on X-ray morphology from the different DM concentrations.
- The physical interpretation is that the greatest dissociation for this system occurs when a high-density bullet (A2034N) crosses a lower density environment. Implying that if the substructures have comparable inner gas densities, the offset is less pronounced.

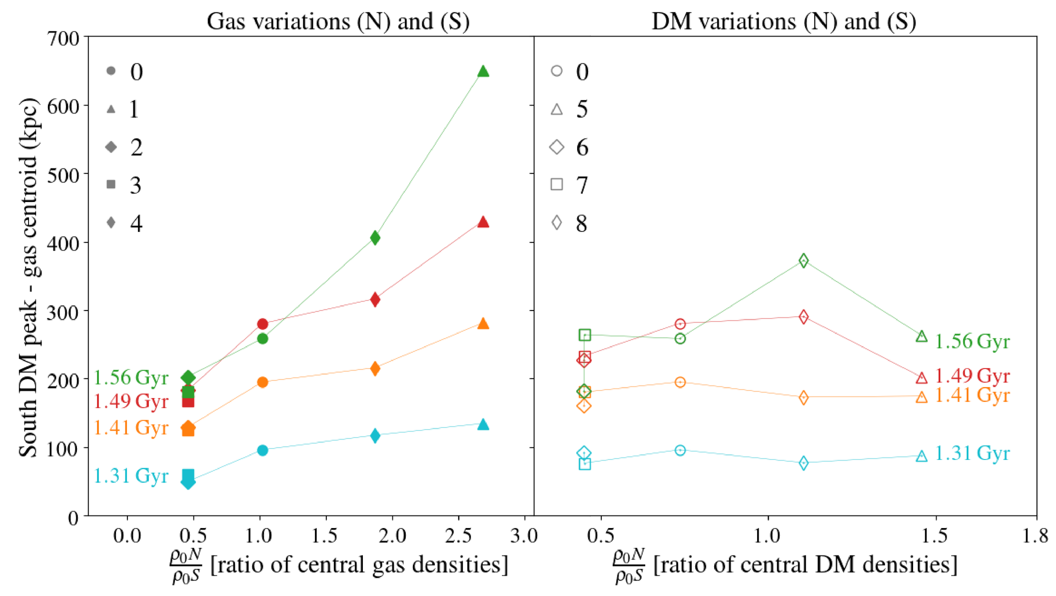

Figure 3. Gas displacement in relation to the southern DM peak in each model. Left: Distance of gas emission centroid to south DM as a function of the ratio of the central gas densities. Right: Distance of gas emission centroid to south DM as a function of the ratio of the central DM densities. The icons in both panels represent the models with different gas and DM scale length and the colours represent four simulation times after the central passage.

4 Conclusion

From a simulation model that describes the dissociation of A2034, we run nine other models with different concentrations of gas and dark matter. Thus, it was possible to investigate only the effect that different concentrations have on dissociation for the configuration of this collision. We conclude that the central gas density ratio is more determinant to produce the offset. An exploration of the parameter space with other bullet-like systems can help answer the question under which circumstances will dissociation occur, and consequently what parameters differ a dissociative collision from a non-dissociative collision system.

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