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Simulating temperature maps of gas sloshing in the galaxy cluster Abell 1644

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Abstract. Clusters of galaxies that have suffered recent collisions exhibit remarkable disturbances in gas morphology seen on X-rays. In particular, non-frontal collisions give rise to the sloshing phenomenon, in which the gravitational perturbation generates a spiral pattern in the gas. This appears to be the case of Abell 1644, a nearby galaxy cluster (z = 0.047) composed mainly by two substructures. The aim of this work is to recover the temperature map of the cluster through numerical simulations and compare the results with observational data, in order to obtain a theoretical model that explains its current morphological features. The initial conditions of both structures observed in A1644 were created following the Hernquist density profile, for the gas distribution and dark matter halo. The simulations were performed using the smoothed particle hydrodynamics (SPH) code Gadget-2. In this study we focus on two scenarios that best match the observed temperature map: Scenario A, an off-axis collision between A1466-S and A1644-N with two clusters of comparable masses; and scenario B, an off-axis collision between A1644-S and a galaxy group, with mass ratio of 10. Preliminary analysis from gravitational weak lensing suggests that this might be a feasible model.

Resumo. Aglomerados de galáxias que sofreram colisões recentes exibem notáveis distúrbios na morfologia do gás, observados em raios-X. Em particular, colisões não-frontais dão origem ao fenômeno de sloshing, no qual a perturbação gravitacional gera um padrão espiral no gás. Este aparenta ser o caso do aglomerado Abell 1644, um aglomerado em redshift z=0.047 composto principalmente por duas subestruturas. O trabalho tem como objetivo reconstruir a história dinâmica do aglomerado através de simulações computacionais, e comparar os resultados obtidos com dados observacionais, de modo a obter um modelo teórico que explique suas características atuais. As condições iniciais de ambas estruturas observadas em A1644 foram construídas seguindo o perfil de Hernquist, para o gás e o halo de matéria escura. As simulações foram realizadas utilizando código Gadget-2. Nesse estudo focamos em dois cenários que melhor reproduzem o mapa de temperatura observado: Cenário A, uma colisão não-frontal entre A1644-S e A1644-N, com dois aglomerados de massas comparáveis; e cenário B, uma colisão não-frontal entre A1644-S e um grupo de galáxias, com razão de massas de 10. Estudos preliminares de lentes gravitacionais sugerem que este é um modelo viável.

Keywords. Galaxies: clusters: individual: A1644 – Galaxies: clusters: intracluster medium – Methods: numerical

1. Introduction

The largest gravitationally bound structures in the Universe are galaxy clusters. In the hierarchical formation scenario objects with smaller masses merge earlier, while more massive objects grow from accretion of minor systems. These collisions induce disturbances in the gas of the intracluster medium (ICM), in the form of shocks and cold fronts, that can be observed in the irregular morphology of the X-ray emission. The ICM is a highly ionized plasma with temperatures of 1 – 10 keV, which produces X-ray emission through thermal bremsstrahlung radiation.

Cold fronts are contact discontinuities, which implies continuous pressure but discontinuous temperature and density. Sometimes a cold front exhibit an interesting spiral morphology that stems from the cluster core and reaches out to large distances. These spiral cold fronts are understood as a consequence of an off-axis collision. In this case the gravitational disturbance makes the gas of cluster center oscillate, resulting in a spiral of dense, cool, low entropy gas that was removed from the cluster core. The sloshing mechanism was proposed by Markevitch & Vikhlinin (2007). Several studies have been performed through hydrodynamical simulations to reveal details of the sloshing mechanism, as seen in Ascasibar & Markevitch (2006) and ZuHone, Markevitch & Johnson (2010).

This spiral pattern is observed in Abell 1644, a nearby galaxy cluster at redshift $z = 0.047$. A1644 is composed mainly by two substructures: a main cluster in the south (A1644-S) with mass of $M_{500} = (3.1 \pm 0.4) \times 10^{14}\ h^{-1}\ \mathrm{M}_\odot$, and a northern sub-cluster (A1644-N) of $M_{500} = (2.6 \pm 0.4) \times 10^{14}\ h^{-1}\ \mathrm{M}_\odot$ (Johnson et al. 2010). The projected separation between clusters is $\sim$ 12.4′, or $\sim$ 700 kpc. These mass estimates are derived from X-ray data and depend on certain equilibrium assumptions. The deepest X-ray data available for A1644 are observations with Chandra (Johnson et al. 2010). Before that, it had been studied in X-rays with observations from XMM-Newton (Reiprich et al. 2004) and Einstein (Jones & Forman 1999).

The aim of this work is to recover the temperature map of the cluster through numerical simulations and compare the results with observational data, in order to obtain a theoretical model that explains its current morphological features.

2. Initial conditions

We consider the collision of two spherically symmetric galaxy clusters, initially in hydrostatic equilibrium. The method for generating initial conditions is similar to those used in Machado & Lima Neto (2015) and Ruggiero & Lima Neto (2017).

The dark matter haloes and gas distributions follow a Hernquist (1990) density profile:

$$\rho_{\mathrm{h}}(r) = \frac{M_{\mathrm{h}}}{2\pi} \frac{r_{\mathrm{h}}}{r(r + r_{\mathrm{h}})^3} \tag{1}$$

where M_{h} is the total dark matter mass, and r_{h} is a scale length. Similarly, M_{g} and r_{g} for the total gas mass and scale length. The initial parameters of the objects used in simulations are summarized in Tab. 1.

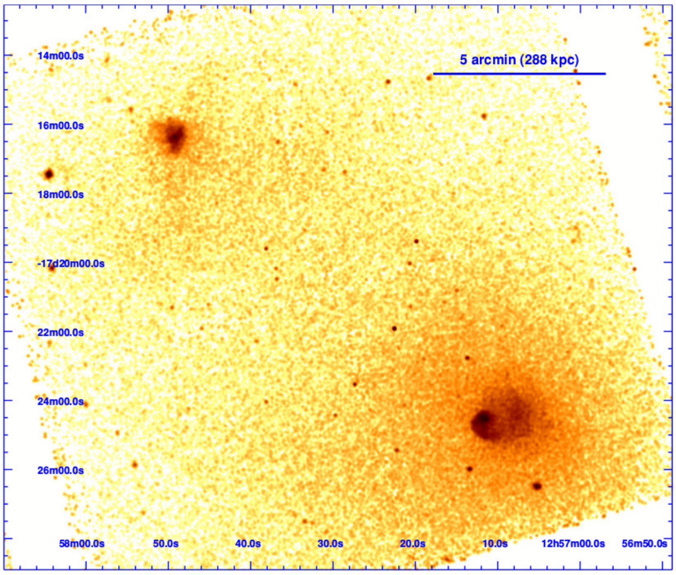

Figure 1. Combined 70 ks Chandra ACIS-I image over the energy range 0.5–2.5 keV. The two bright cores are A1644-N and A1644-S. The spiral pattern of the gas sloshing is seen in A1644-S. Figure taken from Johnson et al. (2010)

Table 1. Initial condition parameters of the simulations.

	$M_{500}(\mathrm{M}_\odot)$	r_h(kpc)	r_g(kpc)	f_{gas}
A1644-S	4.43×10^{14}	550	200	0.13
A1644-N	3.71×10^{14}	500	250	0.13
Group	4.43×10^{13}	210	0	0

In order to explore the parameter space of possible off-axis collisions, a large set of simulations was performed. In this study we focus on two scenarios that best match the observed morphology (Fig.1):

- Scenario A: off-axis collision between A1466-S and A1644-N, with an initial separation of 3000 kpc along the *x*-axis, an initial relative velocity of 1000 km/s, and impact parameter of 1500 kpc.
- Scenario B: off-axis collision between A1644-S and a galaxy group, also with an initial separation of 3000 kpc along the *x*-axis, an initial relative velocity of 600 km/s, and impact parameter of 500 kpc.

Simulations were carried out with Gadget-2 (Springel 2005), a code that represents fluids by means of smoothed particle hydrodynamics (SPH), and the analysis of the output was done using the YT code (Turk et al. 2011). For each scenario, we performed a large suite of simulations, in search of a best-fitting model. Several combinations of parameters were explored, varying initial velocity, impact parameter and inclination.

3. Results

We obtain two preliminary regimes that adequately reproduce some desired features:

The first scenario is where the disturbing subcluster is the northern cluster (A1644- N). In this case, the two clusters have comparable masses and we observe large shock waves that are not present on observational data, as can be seen in Fig. 2. However it was possible to recover the spiral morphology of the gas when the separation between the structures was about 700 kpc. We estimate that A1644 is observed approximately 0.4 Gyr after the pericentric passage, and that the collision axis is inclined by i ≈ 30° with respect to the plane of the sky.

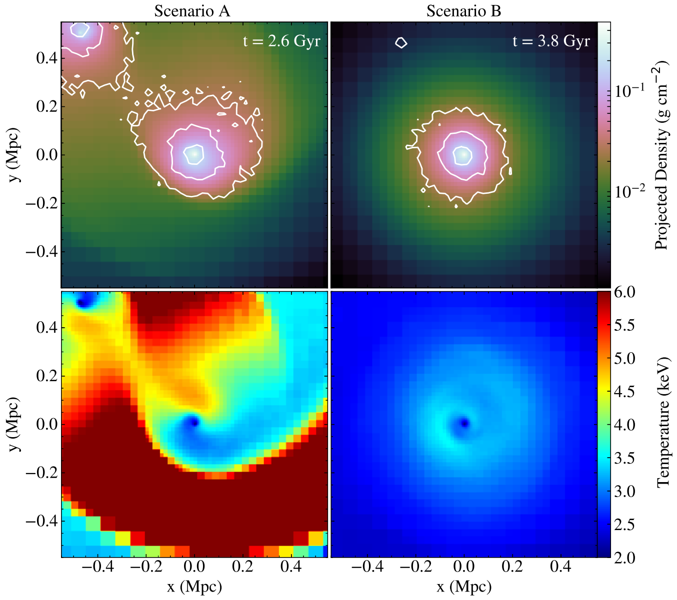

Figure 2. In scenario A, the disturber is the northern cluster. In scenario B, the disturber is a low-mass gasless group. Total projected mass is shown as contours.

In the second case the disturbing subcluster is a gasless galaxy group ~ 10 times less massive than the southern cluster. In this scenario, temperatures are lower and there are smaller shock waves (Fig. 2). The morphology of the gas was recovered when the separation between the structures was about 550 kpc. This is estimated after 1.4 Gyr of the pericentric passage, with the collision axis inclined by i ≈ 60°. Preliminary analysis from gravitational weak lensing suggests that this might be a feasible model. Further simulations are required to reach a more quantitative agreement with observational constraints.

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