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Simulating the gas sloshing of the galaxy cluster Abell 1644 with a recently discovered substructure

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Abstract. The galaxy cluster Abell 1644 exhibits a peculiar morphology in the intracluster medium, in the form of a cold and dense gas spiral that stems from the main cluster's core. This disturbance, known as the sloshing phenomenon, is the result of the gravitational pull in an off-axis collision. In this work, we attempt to reproduce some of the morphological features of the system by means of numerical simulations. The scenarios were simulated through the smoothed particle hydrodynamics code Gadget-2, with the dark matter halo and gas distributions being described by Hernquist and Dehnen density profiles. The study revealed two possible scenarios for the gas sloshing phenomenon seen in the main cluster: the collision between the main cluster and a northern cluster apparently relaxed in X-ray maps, and the collision with a recently discovered structure revealed by weak gravitational lensing analysis. As the merger between similar masses seems to lead to great disturbances in the intracluster medium, the best-fitting model suggests the collision with a subcluster of lower mass that loses its gas after the pericentric passage.

Resumo. O aglomerado de galáxias Abell 1644 exibe uma morfologia peculiar de gás do meio intra aglomerado, na forma de uma espiral fria e densa que emerge do núcleo do aglomerado principal. Essa perturbação, conhecida como o fenômeno de *sloshing*, é o resultado da perturbação gravitacional em uma colisão não frontal. Neste trabalho, busca-se reproduzir algumas das propriedades morfológicas do sistema por meio de simulações numéricas. Os cenários foram simulados a partir do código Gadget-2, com perfis de densidade de matéria escura e gás sendo descritos pelos perfis de Hernquist e Dehnen. Tal estudo revelou dois possíveis cenários para o fenômeno de *sloshing* vistos no aglomerado principal: a colisão entre o aglomerado principal e um aglomerado ao norte aparentemente relaxado em mapas de raios-X, e a colisão com uma estrutura recém descoberta pela análise de lentes gravitacionais fracas. Como a colisão entre massas similares parece levar a grandes perturbações no meio intra aglomerado, o modelo de melhor ajuste sugere a colisão com uma subestrutura de menor massa, que perde seu gás após a passagem pericêntrica.

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

1. Introduction

In the formation scenario of structures, galaxy clusters grows by mergers with minor groups producing irregularities that may become evident in the X-ray emission. In an off-axis collisions, cool-core clusters may develop a spiral cold front through the mechanism understood as "gas sloshing" (Markevitch et al. 2001).

The galaxy cluster presented in the last panel of Fig. 1 is Abell 1644, observed with XMM-Newton (adapted from Laganá et al. 2019). This nearby cluster, at redshift $z = 0.047$, exhibits signs of a recent collision in the intracluster medium. The system is composed of three major structures: the southern cluster, A1644S, that presents a spiral-like structure; A1644N1, a northern cluster nearly undisturbed in the X-ray observations, and A1644N2, a third recently discovered cluster revealed in weak gravitational lensing analysis performed by Monteiro-Oliveira et al. (in prep.).

Johnson et al. (2010) discuss the possibility of A1644N1 being the perturber that triggers the sloshing phenomenon in A1644S after a recent collision event between the two structures. However, a similar configuration may be achieved if a subcluster has its gas stripped in the pericentric passage of a cluster merger.

In this work we review the collision between A1644S/N1 through hydrodynamical simulations and attempt to recover the dynamical history of the system, alongside quantitative and qualitative comparisons to the observational results. We also suggests a new possible perturber to the system: A1644N2 (A more detailed discussion will be presented in a forthcoming paper).

2. Initial conditions

The simulations were performed through the smoothed particle hydrodynamics code Gadget-2 (Springel 2005), with initial conditions created similarly as presented in Ruggiero & Lima Neto (2017). We describe the galaxy clusters as two spherically symmetric structures initially in hydrostatic equilibrium composed by a dark matter halo and a gas distribution. The dark matter follows a Hernquist (1990) density profile,

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

While the gas distribution is described by a Dehnen (1993) density profile,

$$\rho_{\rm g}(r) = \frac{(3-\gamma)M_{\rm g}}{4\pi}\frac{r_{\rm g}}{r^{\gamma}(r+r_{\rm g})^{(4-\gamma)}} \quad (2)$$

where $M_{\rm h}$ is the total mass and $r_{\rm h}$ is a scale length for the dark matter and $M_{\rm g}$, $r_{\rm g}$ for the gas. We use $\gamma = 1$ to describe a galaxy cluster with a cool-core, i.e., a mass model with central density cusp.

3. Discussion

In order to reach a best morphological model, we explored several combinations of initial conditions. The best-fitting model requires: virial masses and radii that corresponds with the preliminary results of the gravitational lensing analysis of Monteiro-Oliveira et al. (in prep.); a cold gas spiral with an extent of

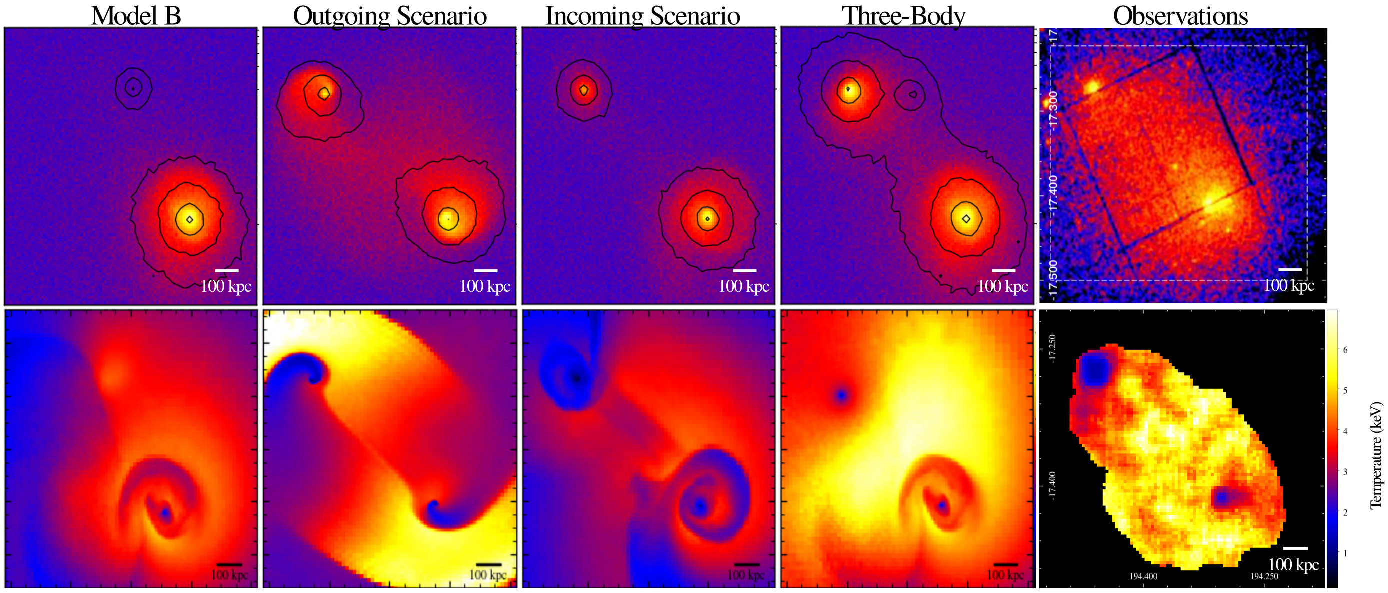

Figure 1. Comparison between simulation models and the XMM-Newton analysis of the galaxy cluster A1644 (taken from Laganá et al. 2019). Top panels: Mock X-ray observations for several collision scenarios. From left to right: A1644S and the recently discovered substructure A1644N2, A1644S and A1644N1 in scenario A, A1644S and A1644N1 in scenario B, three-body simulation, observed X-ray emission (XMM-Newton). Bottom panels: Emission-weighted temperature maps.

~ 200 kpc; Projected separation between the cluster centers of ~ 700 kpc (~ 550 kpc) for A1644S/N1 collision – Johnson et al. (2010) (A1644S/N2 – Monteiro-Oliveira et al. in prep.); A1644N2 should become nearly undetectable in mock X-ray observations.

Fig. 1 present the main results in a comparison between simulation models and the XMM-Newton analysis of the galaxy cluster A1644 (taken from Laganá et al. 2019). The top panels displays the mock X-ray observations for four different collision scenarios. From left to right: the collision between A1644S and the recently discovered substructure A1644N2 (Model B), A1644S and A1644N1 in the first passage (Scenario A), A1644S and A1644N1 in a second approach after apocentre (Scenario B), a three-body simulation, and the observed X-ray emission (XMM-Newton). The bottom panels shows the corresponding emission-weighted temperature maps.

In model B, the disturber is dispersed by tidal forces after the pericentric passage, becoming difficult to identify. This simulation indicates a good agreement with observations, even in the temperature ranges when considering the absence of A1644N1. In scenarios A and B, we try to reproduce the collision between A1644S and A1644N1 in two different time-scales: Scenario A is a recent event after the pericentric passage, displaying a twin spiral morphology and large shock waves that are not present in observations; Scenario B is the evolution of the system after apocentre, in this case lower temperatures are observed (~ 3 keV) and a larger extent of the spiral feature (~ 300 kpc).

The three-body simulation is an attempt to reproduce the presence of the three clusters simultaneously. Its initial condition is model B, 1 Gyr before the best instant, with the addition of A1644N1 arriving perpendicularly to the line-of-sight. This approach gives a very good qualitative agreement to the observations.

4. Conclusions

The best fitting model that seems to reproduce some of the features observed in the galaxy cluster Abell 1644 is the collision between A1644S/N2, where a low mass subcluster has its gas stripped in the pericentric passage. The three-body simulation suggests that A1644N1 may be in a first arrival without interfering in the formation of the spiral feature. The collision scenario between A1644S/N1 seems to lead to a worse agreement to the observations due to great disturbances in the intracluster medium, when both structures have similar masses.

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