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Ram pressure in galaxies crossing sloshing spirals

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Abstract. As galaxy clusters pass near each other in a off-axis collision, a cold gas front may be induced due to interactions between them, a phenomenon called *sloshing spiral*. This spiral is composed of cold and low entropy gas removed from the cluster core, forming discontinuities in temperature and density. We aim to explore differences in galaxy properties as it crosses the sloshing in order to understand what effects such discontinuities in the intracluster medium can have in a galaxy. With this intent, N-body simulations were used, first inducing a cluster collision and then inserting a galaxy that would cross the spiral. Star formation rate and the total gas amount in the galaxy are analyzed, comparing it to a control galaxy, getting results showing that the galaxy loses more gas as it aproaches the discontinuity and has a reduced star formation rate compared to the control galaxy.

Resumo. Quando aglomerados de galáxias passam próximos uns dos outros, uma frente de gás frio pode ser induzida pelas interações entre eles, chamada de *espiral de sloshing*. Essa espiral é composta de gás frio e de baixa entropia retirado do núcleo do aglomerado e tende a formar descontinuidades no perfil de temperatura e densidade. Neste trabalho é procurado explorar as diferenças nas propriedades de uma galáxia que cruza o *sloshing*, tentando compreender que efeitos cruzar tais descontinuidades no meio intra-aglomerado pode causar na galáxia. Para isso, foram utilizadas simulações de N-corpos onde uma colisão de aglomerados é induzida e, posteriormente, uma galáxia é inserida de forma a cruzar a espiral. São analisadas a taxa de formação estelar e a quantidade total de gás na galáxia inserida, a comparando com uma galáxia de controle, obtendo resultados apontando que a galáxia cruzando o *sloshing* perde mais gás ao se aproximar da descontinuidade e tem uma formação estelar reduzida nessa região em comparação com a galáxia de controle.

Keywords. Galaxies: clusters – Galaxies: clusters: intracluster medium – Galaxies: evolution

1. Introduction

Cold gas fronts can be observed in galaxy cluster collisions with a significant impact parameter, called sloshing spirals (SS) due to their characteristic shape (Ascasibar & Markevitch 2006). These SS are composed of cold gas removed from the cluster's core, imposing discontinuities of temperature along the intracluster medium (ICM).

It is known that the environment can deeply affect galaxy evolution, such as the phenomenon of ram pressure stripping (RPS), common in galaxies crossing the ICM. In this process the hydrodynamical pressure caused by the ICM can effectively strip gas from the galaxy, changing its properties (Gunn & Gott 1972; Steinhauser, Schindler, & Springel 2016).

Numerical simulations have already been employed in order to study SS (ZuHone 2011; Ascasibar & Markevitch 2006), nonetheless, it isn't well established the specific impacts it could induce onto a galaxy that crosses the discontinuities it presents.

With this study we aim to analyze such effects in galaxy evolution caused by the SS, evaluating star formation rate and the stripped gas by RPS.

2. Methods

2.1. Code and base parameters

In order to simulate all interactions GADGET-4 was used, a N-body simulation program that implements smoothed-particle hydrodynamics and star formation models (Springel et al. 2021). Moreover, this code also has the option of using an analytical gravitational profile which lessens computational cost, since it is possible to replace all dark matter in one of the objects simulated. The galaxy and all clusters used were generated using Python 3 ported versions of CLUSTEP and GALSTEP, programs originally described and used in (Machado & Lima Neto 2013) (Ruggiero & Lima Neto 2017).

Table 1. Cluster parameters used. The scale lengths are related to the density profile of their respective component and correspond to the scale lenght in Hernquist (1990) profiles.

Cluster	A	B	C
Total mass ($M_\odot$)	4×10^{14}	8×10^{13}	3.5×10^{14}
Halo scale length (kpc)	355	230	355
Gas scale length (kpc)	190	125	190

Specific scale and mass parameters used for the clusters are shown in Table 1. Properties of clusters A and B were chosen such that they would have 15% of the total mass composed of gas. Cluster C was created specially to induce the same initial evolution observed in the galaxy that crosses the SS onto the control galaxy, implying in it having only 3% of gas from the total mass. The galaxy was generated with a dark matter halo with mass 10^{12} $M_\odot$ and 9×10^{10} $M_\odot$ of baryonic mass, composed of $\sim$ 35% gas. Furthermore, particle amounts were chosen so that the ratio mass/particle was kept similar between the galaxy and the clusters, limiting simulation size to $\sim 10^7$ particles with a ratio $\sim 5 \times 10^4$ $M_\odot$ per particle with the available computational power.

2.2. Simulation setup

In the first simulation a SS was generated. Clusters A and B were relaxed and placed 3 Mpc apart along the x axis on simulation cartesian coordinates, having relative velocity $\mathbf{v} = -1000\,\hat{x}$ km/s and an impact parameter of 500 kpc.

From the first simulation a snapshot is chosen when the SS is well defined (Fig. 1), being used as a base for inserting the

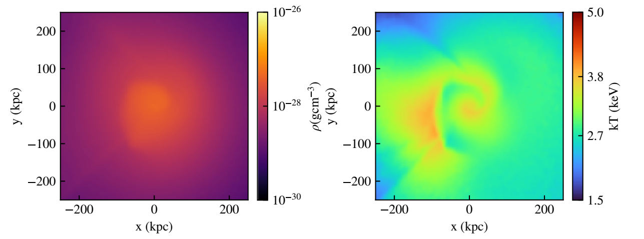

Figure 1. Cluster collision visualization at the chosen time for galaxy insertion, where the SS can be distinguished from the environment. A density and a temperature map from left to right, where both used a slice in the xy plane emphasizing the discontinuities.

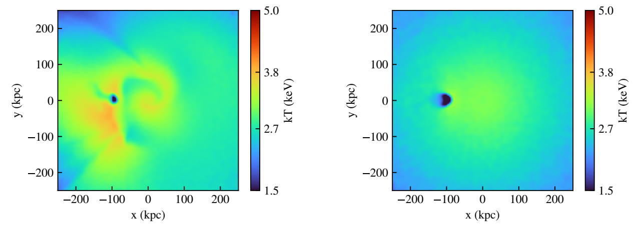

Figure 2. Temperature maps centered at the main cluster when the galaxy from the second simulations starts crossing the SS. The cluster with SS is at the left, while the undisturbed cluster is at the right. In both cases the galaxy can be identified as the bluest region near $(-100, 0)$ kpc.

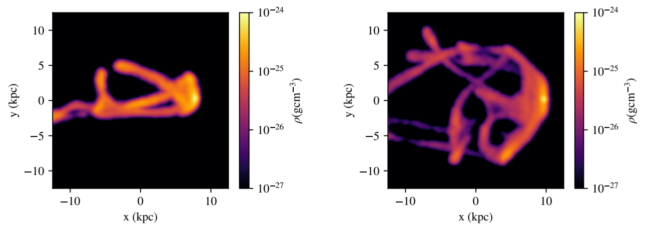

Figure 3. Density maps centered at the galaxies when falling into the cluster at the same moment. At left is the galaxy from the disturbed cluster simulations after crossing the sloshing. To the right the galaxy that enters the undisturbed cluster.

galaxy at $x = -200$ kpc with velocity $\mathbf{v} = 500\,\hat{x}$ km/s, effectively crossing the SS and its discontinuities.

Finally, a third simulation was conducted, where the same initial galaxy enters a non-disturbed cluster (C). The galaxy is inserted with the same dynamical properties as the last one, having a similar evolution until interacting with the SS. This simulation was used as a control for comparison.

3. Results and Analysis

For comparing the specific regions where the galaxies traverse in each simulation, a cylindrical volume of radius 50 kpc along their trajectory was considered, making explicit the differences between the clusters when plotting the temperature and density over the cylinder length, Fig. 4, clearly showing the region with discontinuities. Also, as a means to analyse the galaxies, the total gas and star formation rate were measured using a disk of height 5 kpc encompassing the galaxy, creating Fig. 5.

From these quantities, the a) panel in Fig. 4 suggests that as the galaxy gets closer to the discontinuities, it tends to lose more gas in relation to the galaxy falling onto the undisturbed cluster. Moreover, the b) graph in Fig. 5 suggests that the interaction with the SS also quickly diminishes star formation rate in the galaxy since more gas is lost when crossing the SS, while the control galaxy maintains a relatively constant star formation rate.

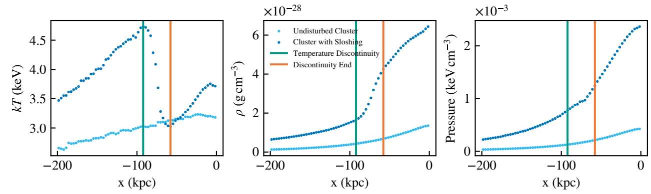

Figure 4. Gas properties over a cilyndrical tunnel aligned with the galaxy trajectory in both simulations. From left to right, a temperature profile, a density profile and a pressure profile. Vertical lines are drawn at the beginning and ending of the discontinuities using the temperature profile as reference.

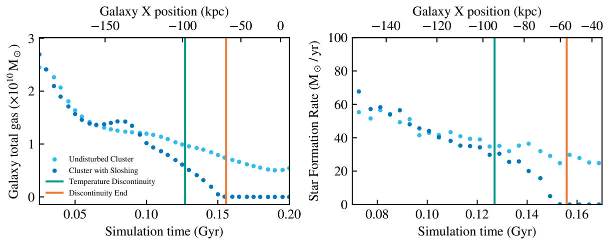

Figure 5. Galaxy properties. Left graph has the measurements of total galaxy gas over time and position; the right graph presents star formation rate. Vertical lines are drawn at the beginning and ending of the discontinuities using the temperature profile as reference.

4. Conclusions

We aimed to understand what kind of impacts on the evolution of a galaxy traversing a disturbed intracluster medium with SS can cause. Results suggest that in these conditions the galaxy that crosses the SS tends to lose more gas, also exhibiting a decrease in star formation rate in relation to a control galaxy. Furthermore, star formation rate and gas lost quantities were consistent with previous simulations of ram pressure stripping using the same initial condition creation process.

It is possible that future simulations with better mass resolution could enable different types of analyses, increasing the reliability of current conclusions. Additionally, a systematic exploration from the parameter space of the SS correlated with galaxy properties could improve the understanding about more specific impacts on galaxy evolution.

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