Merging of Quenched Dwarf Galaxies

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1 INTRODUCTION

Whether mergers of dwarf galaxies can trigger star-formation is still unclear. Many observations suggest that mergers can fuel star-formation. Observations on NGC4809/4810, a merging pair of dwarf galaxies, shows star-formation in the interacting area (Gao et al. (2023)). Another survey on S0 galaxies that are known to be in general non-star forming finds some special S0 galaxy whose star-formation has been rejuvenated. In this research, Rathore et al. considers minor mergers as the main contributor to their strange star-formation rate(SFR) (Rathore et al. (2022)). Other research, however, argues that mergers cannot trigger star-formation or even quench a galaxy. Going through Sloan Digital Sky Survey data, Li et al. points out that galaxy mergers exert a minimal impact on their specific SFR, while the star formation efficiency of gas-rich, minor mergers even appears suppressed (Li et al. (2023)). Pearson et al. also suggest that galaxy mergers have little effect on the SFR of the majority of merging galaxies compared to the non-merging galaxies(Pearson et al. (2019)). Previous research has even identified merging as a potent mechanism for quenching of star-formation(Croton et al. (2006)).

The most interesting question is, why observation has shown starbursts in mergers, while merging is generally considered to be a star-forming quencher. Observations attribute the decrease in SFR for post-starburst galaxies to the consumption of molecular gas by the starburst(Baron et al. (2023)). However, a starburst is rare even for a merger, especially there are no starburst found in gas-rich major merger(Li et al. (2023)).

To simplify the problem, star being formed is not simulated but we are just looking out for places where gas is dense enough for star formation to occur. As stars are born from gas, whether merging can fuel star-forming is depending on the gas distribution during and after the merging process. We will consider two identical gas-poor dwarf galaxies and merge them together and observe the gas distribution during the merging process. We expect to see an increase in density during the interacting stage, and we hope to see higher densities after the merger compared to before the merging if merging actually rejuvenates star-formation.

2 METHODS

2.1 Amuse packages used

Smoothed-particle hydrodynamics

For the gas particles, we required a hydrodynamical code. We chose the SPH code Fi for this purpose. In practice we need small enough particles to be able to resolve densities that are high enough.

Barnes-Hut tree

For dark matter and stellar matter background in which we simulate the gas particles, we chose to use the bh-tree package of amuse. A Barnes-Hut tree is a very useful code for a galaxy merger as it lets the two galaxies treat each other as point-particles at far enough distances, while still giving sufficient precision for particles that are close to each other. Generally speaking, a the time it takes to run a Barnes-Hut tree with n particles is proportional to $n\log(n)$ compared to a direct n-body code whose time is proportional to n^2.

Bridge

In order to couple the hydrodynamical code of the gas particles with the N-body gravitational code of the galactic background, we require a bridge. Since the total gas has significant mass, there is not only a bridge from the gravity to the hydrodynamics code but also one from the hydrodynamics code to the gravity code.Pelupessy et al. (2013)

2.2 Initial conditions

One of the hard parts of simulating merging galaxies is getting the initial conditions just right, especially when trying to get a minor merger. The very basic idea of how the desired setup for the galaxy merger looks can be seen in figure 1. The figure shows two galaxies where their stars are shown as red for galaxy one and blue for galaxy two. Yellow represents gas which can be used for star formation and is concentrated around the galaxies centers. Since the galaxies are supposed to represent dwarf galaxies which are elliptical they do not have a disc like for example the Milky Way, but are instead spheres. Likewise the gas is set up as a spherical gas cloud. The galaxies are placed apart from each other in both the x and y plane so that they only need a initial velocity in one direction in order to make both minor and major mergers. Since they pull on each other with gravity they will make a major merger if they have no initial velocity, but if they have a very high initial velocity they will pass each other with no merging. Any velocity in between will result in some kind of merger. Figure 2 shows the galaxies merging mixing part or all of the gas they have. Since both major and minor mergers are wanted the initial velocity is a parameter that is varied from simulation to simulation. The force of gravity between the galaxies is dependant on their total masses. To keep the galaxies quenched we stick to a ratio of about 10 times more stellar matter than gas and since dwarf elliptical galaxies generally have a stellar mass of up to $10^9 M_\odot$, and more gas might better show star formation $10^8 M_\odot$ of gas was chosen. The sizes of galaxies are usually in order of kilo-parsecs even for dwarf galaxies and so the galaxies are set to 3 kilo-parsecs in radius with a separation distance of around 45 kilo-parsecs. In most cases a merger will happen after about 1000 Mega-years, but in order to make sure the galaxies can evolve to a new equilibrium and to see if any would be minor

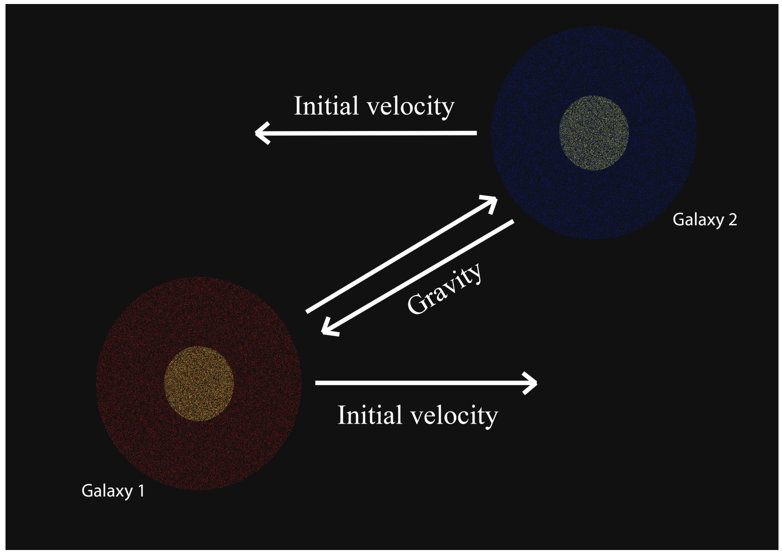


Figure 1. Sketch of the initial setup of the simulation. Two galaxies, made up of stars (blue/red) and gas (yellow), both with some initial velocity in the x-direction and gravitational pull on each other determined by their total mass.

mergers evolve into a major merger a simulation end time of 3000 Mega-years fits. The last variable to set is the number of particles that will represent the total mass of the galaxies, both of gas and for stars, this mostly comes down to how much computer power is available. Since something that works at smaller scale and can run on a laptop in a reasonable time, 20000 stars and 10000 gas particles are used.

3 RESULTS

With the initial conditions mostly set, except for the initial velocity, this section shows the results of the simulation, what kind of mergers are seen and whether or not stars be formed from the gas.

Illustrating the stars and gas is somewhat simple as the simulation tracks all their positions, but given that we are only interested in whether or not star formation can occur seeing the gas density is much more useful than just its position. In figure 3 is an example of how a merger is visualized by the code, the blue particles are the 20000 stars and the gas is colored according to its relative density, which simply show where the most gas is. In total 60 snapshots are taken per run so that everything evolves 50 Mega-years in between each snapshot.

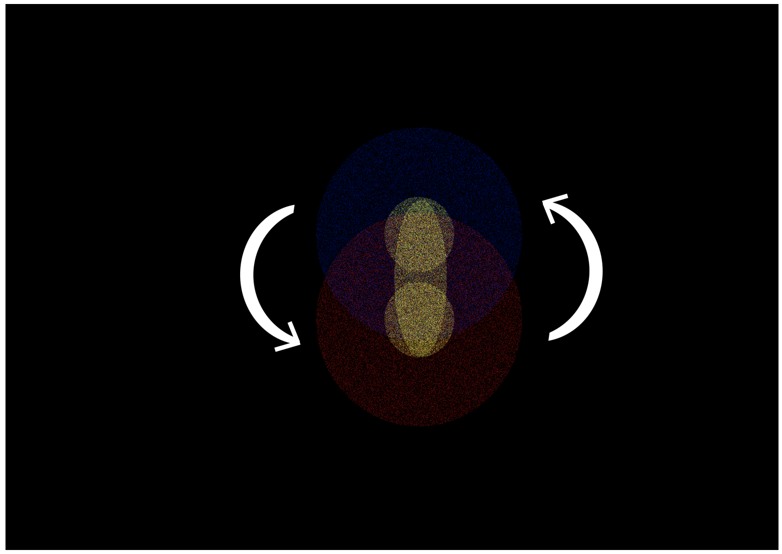
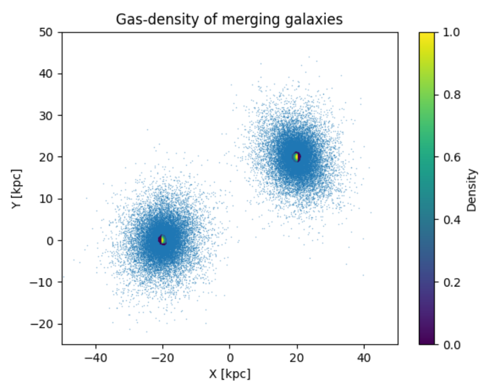
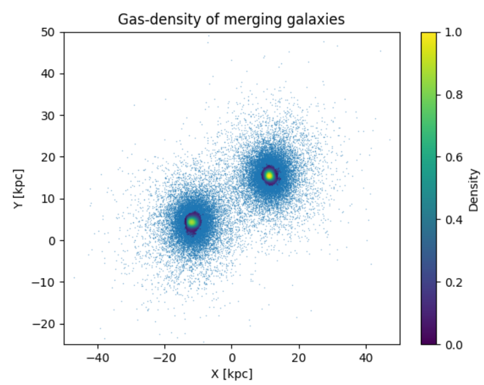


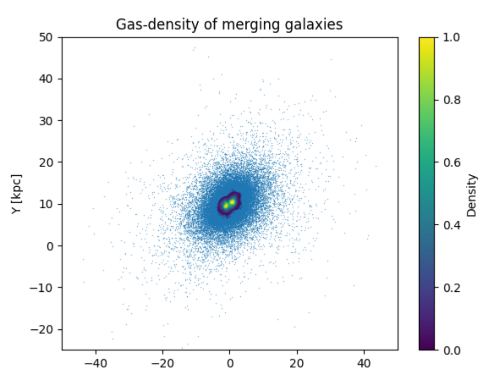
Figure 2. Sketch of the two galaxies merging by having the gas spheres mixing. This should either result in a major merger where they end up as one bigger galaxy after, or a minor merger where they separate again and stay two galaxies.



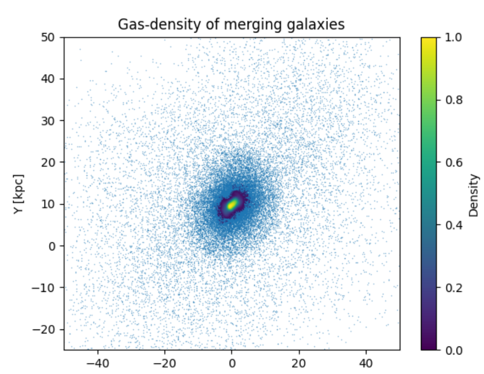
(a) Snapshot: 50Myr



(b) Snapshot: 500Myr



(c) Snapshot: 650Myr

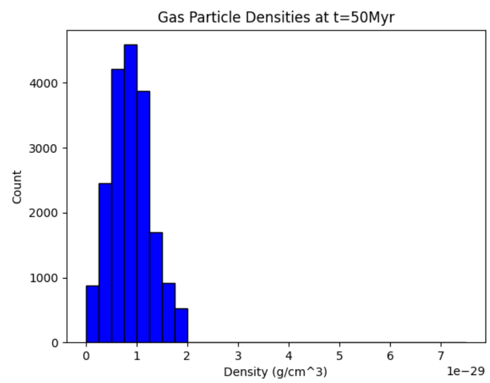


(d) Snapshot: 1100Myr

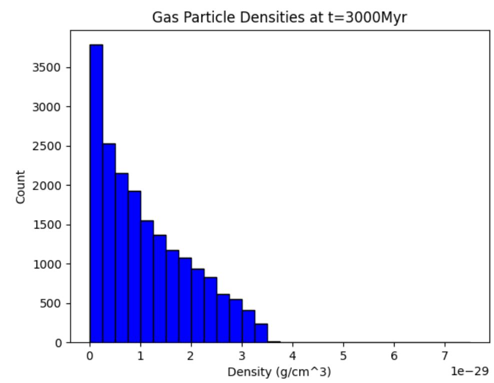
Figure 3. Gas density plots of dwarf galaxies merging. Both galaxies move towards each other in the x-direction with a speed of 0 km/s resulting in a major merger.

In figure 3 there are four snapshots of the simulation where both galaxies have a initial velocity of 0 km/s. Because of this the two galaxies simply move straight towards each other, resulting in a major merger after about 1000 Mega-years. Figure 3a and figure 3b show the approach of the galaxies, whereas figure 3c show the first pass they do of each other before merging and looking like figure 3d. This type of merger leaves everything pretty stable and very little mass is flung out from the new galaxy. The head-on collision is also the best bet for star formation since the centers of both gas clouds ram into each other.

In order to see if there is a possibility of star formation in this merger, the densities of the gas are plotted as a histogram with the density out the x-axis as can be seen in figure 4.



(a) Snapshot: 50Myr



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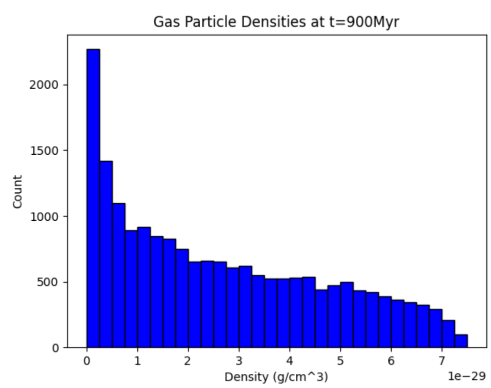
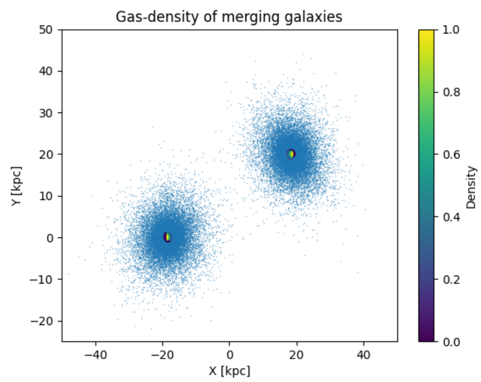


(c) Snapshot: 900Myr

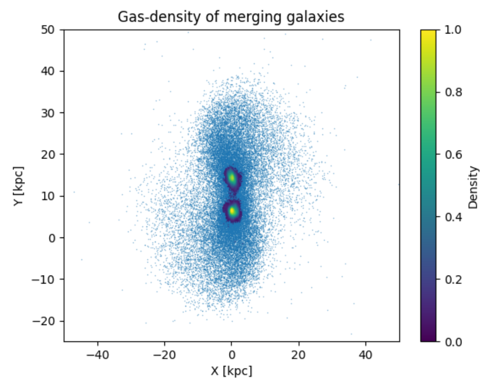
Figure 4. Histograms for major merger of dwarf galaxies with initial velocities by the galaxies of 0 km/s

The three histograms show the densities of the beginning of the simulation (figure 4a), the end of the simulation (figure 4b) and the snapshot where the density is the highest (figure 4c). In the beginning it is expected that the density look very similar to a Gaussian which figure 4a does, the densities are overall very low and it is safe to say that the galaxy is quenched. As the merger happens around 900 Mega-years in this is where the largest densities are seen, with some parts close to four times as dense as the initial density, seen in figure 4b. Whether this is enough for star formation will be talked about in the discussion section. Then as it evolves the density slowly falls over time but still some bits remains quite a bit denser than the initial density, seen in figure 4c.

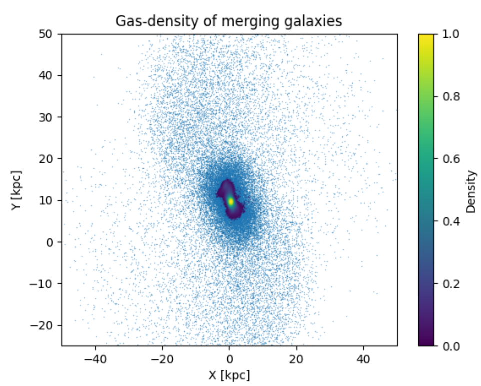
Varying the initial velocity to 30 km/s the simulation evolves quite differently although ultimately it is still a major merger like before. Figure 5 again shows how the stars and gas moved during the simulation.



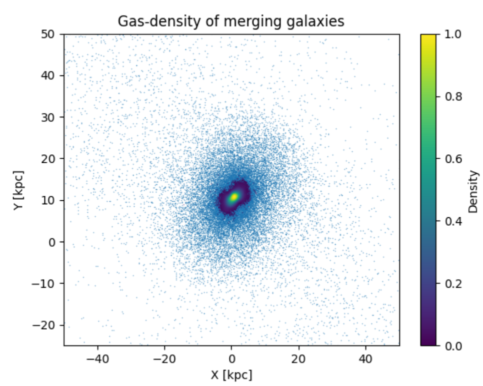
(a) Snapshot: 50Myr



(b) Snapshot: 600Myr



(c) Snapshot: 800Myr

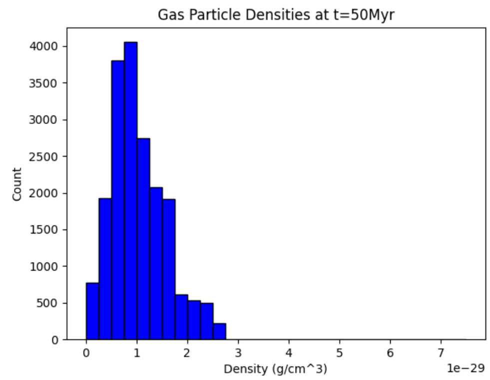


(d) Snapshot: 1500Myr

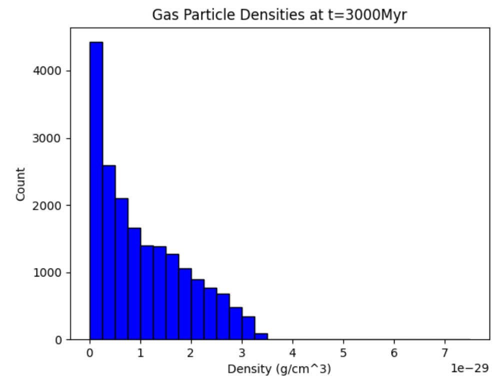
Figure 5. Gas density plots of dwarf galaxies merging. Both galaxies move towards each other in the x-direction with a speed of 30 km/s resulting in a major merger.

Here figure 5a shows the initial state of the simulation again, figure 5b shows how instead of hitting each other head on they move around each other slowly merging the gas. Figure 5c shows how the added angular momentum to the system throws more star matter away giving a generally more chaotic merger. Lastly figure 5d shows that this was indeed a major merger and we are left with one galaxy.

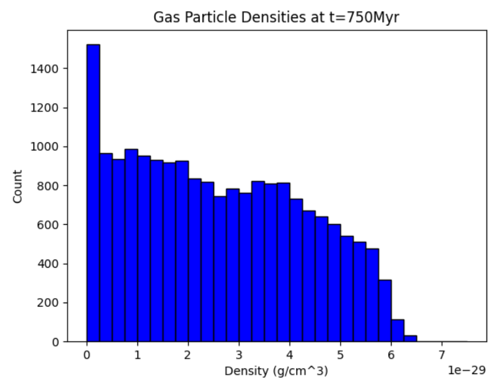
Again looking at the histograms to see what kind of densities where achieved. The slower merging of the galaxies should lower the peak density but maybe it will leave the density higher as it evolves.



(a) Snapshot: 50Myr



(b) Snapshot: 3000Myr

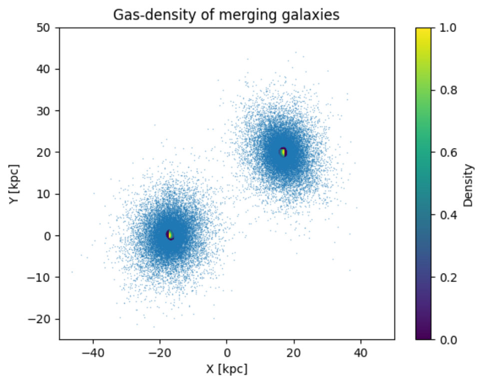


(c) Snapshot: 750Myr

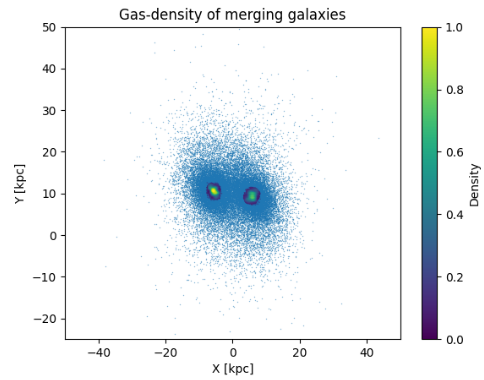
Figure 6. Histograms for major merger of dwarf galaxies with initial velocities by the galaxies of 30 km/s

In figure 6a the initial densities again follw a Gaussian mostly. During the merger the peak densities are the ones shown in figure 6c, the densities seem more evenly spread out while almost reaching the same peak as the head on collision. After a while the densities follow figure 6c where, again the slow drop of can be seen, but also how here many more ended in the bottom bin in a very not dense region.

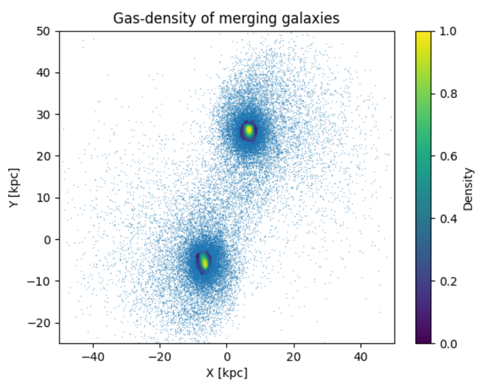
If the initial velocity is increased even more to 60 km/s the results are quite different. Figure 7 shows how this time the result is a minor merger where the two galaxies both start and end up apart from each other, but do merge and share some of the outer gas bubble with each other.



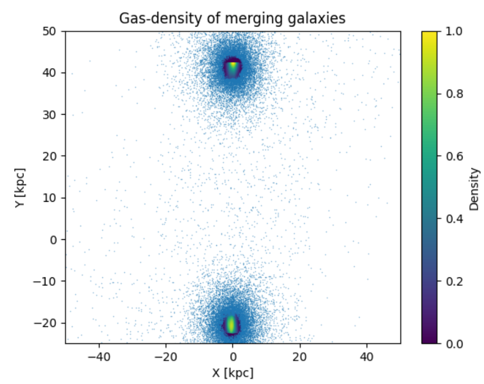
(a) Snapshot: 50Myr



(b) Snapshot: 350Myr



(c) Snapshot: 600Myr

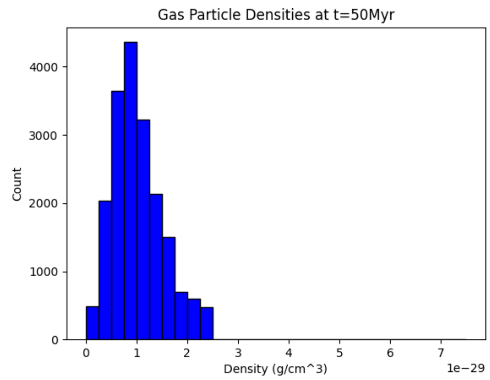


(d) Snapshot: 1100Myr

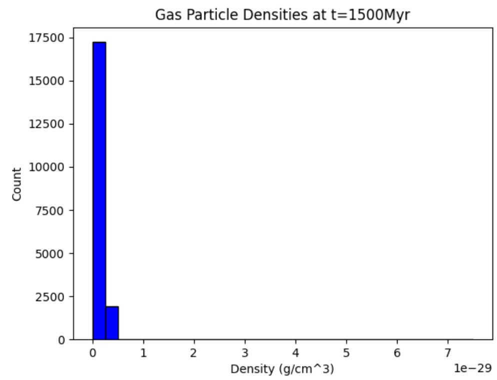
Figure 7. Gas density plots of dwarf galaxies merging. Both galaxies move towards each other in the x-direction with a speed of 60 km/s resulting in a minor merger.

The first figure is again initial state. As they move quite fast figure 7b show their closest approach, just gracing each other and then in figure 7c throwing quite a bit of stars away. After that they very slowly drift away as seen in figure 7d.

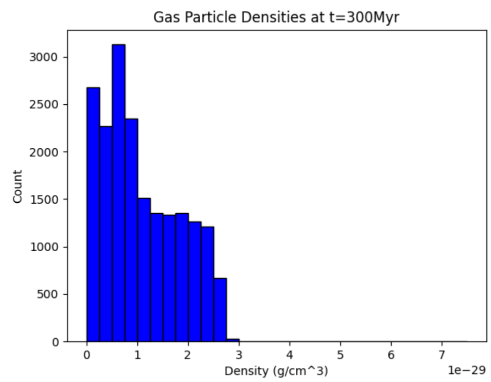
Since this is a minor merger the peak density is expected to be much lower than the other twos.



(a) Snapshot: 50Myr



(b) Snapshot: 1500Myr



(c) Snapshot: 300Myr

Figure 8. Histograms for minor merger of dwarf galaies with initial velocities by the galaxies of 60 km/s

The initial histogram still mostly follows a Gaussian as expected. After 300 Mega-years there is the peak density that is, as expected a good bit lower than the other twos, seen in figure 8c. After a while the density in this simulation has dropped to almost nothing suggesting that quite a bit of gas has been striped from both galaxies, seen in figure 8b

4 DISCUSSION

In order to estimate whether the gas is dense enough to form stars, we can compare the density values of our simulation to what densities are generally expected for a molecular cloud to form stars. In Mo et al. (2010), a typical density value of $10^{-19}\frac{\mathrm{g}}{\mathrm{cm}^3}$ is mentioned as the point where star formation starts occurring. While the actual value of the Jeans density is dependent on both the temperature of the gas as well as its chemical composition, for the purposes of this project, an approximate order of magnitude is sufficient for us to compare it to our data.

Now, as one can see on the x-axis of the histograms, the densities that we reach in our simulation are only around $10^{-29}\frac{\mathrm{g}}{\mathrm{cm}^3}$. That is 10 orders of magnitude lower than what we would expect for successful star-formation! Unfortunately this suggests that our simulation has way to low of a resolution of the SPH gas particles to be able to draw any quantitative conclusions about whether or not the merging of dwarf galaxies can induce star formation.

Qualitatively, there is a clear increase in the peak densities during the two major merger events as one can see in figures 4c and 6c. This doubling to tripling of the maximal densities at the time of a merger could be an indicator that a starburst occurs during the merging event. The code used for this project could be used in the future on a high-performance computer to test this hypothesis further at a much higher gas resolution.

We acknowledge that galaxies may still be quenched even if they have plenty of cold gas and do not form stars efficiently(Luo et al. (2020)). Our model does not take into account the complexities in the mechanism behind star-formation. Another more in depth way to study the effect of merging-triggered star-formation would be to include code that produces stars from the gas cloud, but we do not include any stellar code in our model.

From the histograms, it can be see that some gas is lost in the merger. The left most bin in the histograms includes the particles that are in an environment with a density approaching zero. This effect is the strongest in figure 8b, the final stage of the minor merger. As such the minor merger strips the galaxies of the gas that they had and thus quenched them more than they already were.

5 CONCLUSION

In summary, the simulation shown is not of a high enough resolution to accurately predict whether or not star-formation would occur in the merging dwarf galaxies. There are signs that minor mergers between galaxies can strip them of some of their gas while major merger seem to keep more of it.

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