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Morphological Changes in Galaxies Caused by Relatively High-Velocity Collisions

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Abstract. Here we provide an overview of the morphological modifications in galaxies caused by galactic collisions. Collision-induced features such as tidal waves can either become self-gravitating structures that may end up in dwarf tidal galaxies, or remain in the gravitational field of the parent galaxy to produce pseudo-circular features. Because of the collision-induced shock waves, such features are likely formed by an increase in the density of both existing stars and the inter-stellar gas, the latter ending up in bursts of star formation. The circular features are unlikely to survive a second encounter with another galaxy, however, and the outcome of multiple collisions between galaxies in a cluster is expected to be an elliptical object with a compact central nucleus. Multiple collisions can involve a couple of galaxies if their masses are high enough and their relative velocity low enough so as to allow them to remain gravitationally bound after the first collision event. In this case, deep morphological changes are expected to take place. If collision involves galaxies of different mass, the larger one is expected to strip material out of the smaller galaxy. Finally, our simulations of galactic collisions allowed us to reproduce the streams and inter-galactic bridges that are observed in the interacting Magellanic Clouds.

Keywords: Galactic collisions; star formation; galaxy harassment; galaxy clusters; gas stripping; inter-stellar medium.

1 Introduction

Galactic collisions are major events that deeply affect the morphological evolution of galaxies within clusters. It has been known for many years that young clusters are rich in spiral galaxies while older ones are much richer in elliptical galaxies, and collisions play a very important role to induce these morphological changes in time [1,2]. Moreover, collision events also cause abrupt modifications in the inter-stellar medium within galaxies, with important consequences on the star formation rates [3]. Indeed, compression waves may increase the gas density of the inter-stellar medium and favour the collapse of gas to form new stars. Because newly formed massive stars are very bright but they emit radiation for relatively short times [4], galactic collisions may introduce deep alterations in morphology that evolve with time.

Several features may deeply influence the outcome of collision events and affect the formation of new structures. For instance, collisions with low enough velocity can cause galactic mergers where two colliding galaxies end up into one larger galaxy [5-12]. In other cases, material ejected during the collision or during an interaction in a close encounter can escape the gravitational field of the parent galaxy. This material initially has the form of a long tidal tail but it may evolve into a tidal dwarf galaxy if it becomes a self-gravitating structure [13,14].

The collision velocity, together with the masses of the involved galaxies and the geometry of the encounter (i.e. the positions and the velocity vectors of the colliding objects) plays a major role in defining the collision outcome. Between the two extremes of galaxy mergers (low velocity) and “simple” collisions that affect the morphology (also called galaxy harassment, taking place at relatively high velocity) there is the intermediate case of collisions that, while not ending up in mergers, still maintain a gravitational bond between the two objects after the encounter [2]. This situation enables multiple collisions/interactions to take place. In this context, it is a lucky circumstance that the two small satellite galaxies of the Milky Way (the Small and Large Magellanic Clouds) are actually undergoing such a multi-collisional phenomenon [15-18]. Considering that structures within and among the

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Magellanic Clouds are relatively easy to be observed by multiple techniques due to their relatively short distance, these two objects can provide a very interesting test of the model predictions concerning colliding galaxy couples, particularly as far as the predicted morphological features are concerned.

The goal of this work is to provide a model insight into the effects of different parameters (mass, velocity, and initial galaxy type) over the morphological changes in galaxies due to a relatively high-velocity collision. Therefore, galactic mergers are out of the scope of this paper but galaxy couples that collide several times are taken into account. Attention is also given to the fate of structures that are formed upon a collision event, in the case that a second such event takes place afterwards.

2 Methods

The simulations of galactic collisions were carried out with the Colliding Galaxies software [19]. The relevant simulations show the visual appearance of each galaxy from visible-light emission, thus the star distribution changes will mainly be discussed here. The reported galaxy pictures are single frames from a movie generated by the software, taken at representative timings of the collision event. In the pictures, the two Galaxies are identified with the symbols "%" and "&" to facilitate their identification in a picture series. The default input parameters of the simulations were as follows: mass, 1010 M⊙ for both interacting galaxies; initial position of the "%" galaxy, initially on the picture left side (the position is referred to the origin of coordinates that lies approximately in the centre of each figure), x = -1.3 · 104 parsec, y = -1.0 · 104 parsec, z = 4.7 · 102 parsec; initial position of the right-side galaxy ("&"), x = 1.9 · 104 parsec, y = 1.3 · 104 parsec, z = 7.0 · 102 parsec; initial velocity vector of "%", vx = -85 km s–1, vy = 75 km s–1, vz = 5 km s–1; initial velocity vector of "&", vx = -75 km s–1, vy = -25 km s–1, vz = -30 km s–1. In preliminary simulation runs, these initial conditions proved to be able to produce effective interactions and collisions. Further input parameters, including modifications of the default ones, will be specified whenever relevant (see figure legends). The simulation of the evolution of stars with different masses was carried out with the StarClock software [20], based on stellar model grids provided by Schaller and coworkers [4].

3 Results and Discussion

Among the important changes that collisions would cause in galactic morphologies, a major one concerns the shape of the arms of spiral galaxies as well as the aspect ratio between the arms and the central nucleus [2]. Figure 1 shows a modelled collision between two spiral galaxies (of the kind Sc + Sc for 1a and SBb + SBb for 1b), which produces deep modifications in the arm structure and causes the central nucleus of both galaxies to acquire higher importance compared to the spiral arms. Similar results are obtained when modelling the collisions between different spiral and barred spiral morphological types. The gradual transformation of spiral into elliptical galaxies is an expected result as far as data of galactic evolution within clusters are concerned, considering that young clusters are rich in spiral galaxies while the older clusters contain a higher proportion of elliptical galaxies, likely formed through collisions [2].

Galactic collisions produce tidal tails that under given circumstances may become self-gravitating structures of approximately 109 M⊙. These structures finally produce tidal dwarf galaxies, although the actual importance of such a galaxy formation process is still under debate [2,13,14]. The Figure 1 simulation shows tidal waves that remain gravitationally bound to the parent galaxy in the form of circular features surrounding the galactic centre. A similar issue can be observed upon collision between two elliptical galaxies (see Figure 2). The high density of stars in these tidal formations can be the consequence of compression waves operating on the already existing stars and/or on the gas, in the latter case inducing outbursts of star formation. Most of the radiation energy emitted by newly formed stars is expected to be produced by the most massive and short-living ones, while less massive stars account for a much lower fraction of the total radiation [4].

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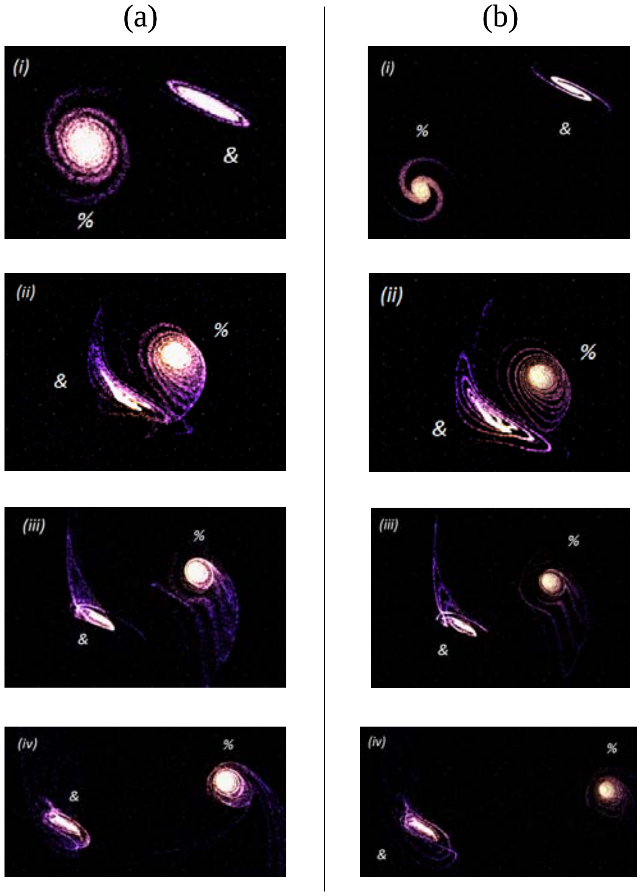

Figure 1. Simulated collision between (a) two Sc galaxies and (b) two SBb galaxies of equal mass (1010 M☉).

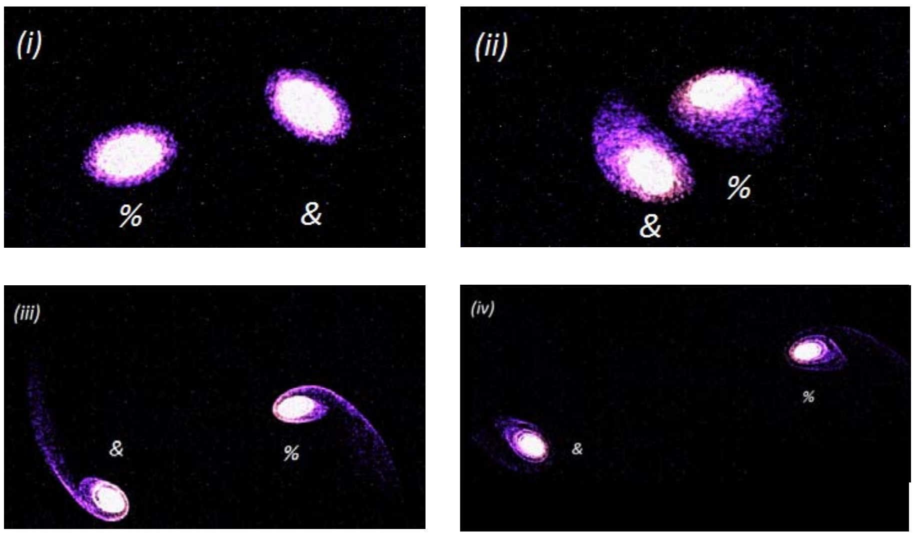

Figure 2. Simulated collision between two elliptical galaxies of equal mass (1010 M☉).

A simulation of star formation and evolution timing is provided in Figure 3. Here it is shown that very massive stars (e.g. 25 M☉) have already formed in a few tens thousands years, after which time smaller gas clouds have not yet undergone gravitational collapse to form the least massive stars. The

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"life cycle" of the most massive stars reaches completion in a few millions years, and after ~20 Myr there would be no longer active stars with mass > 10 M☉ in the originally perturbed gas clouds. Still, the newly formed massive stars would emit radiation for long enough to produce relatively brilliant structures during and soon after a galaxy collision event.

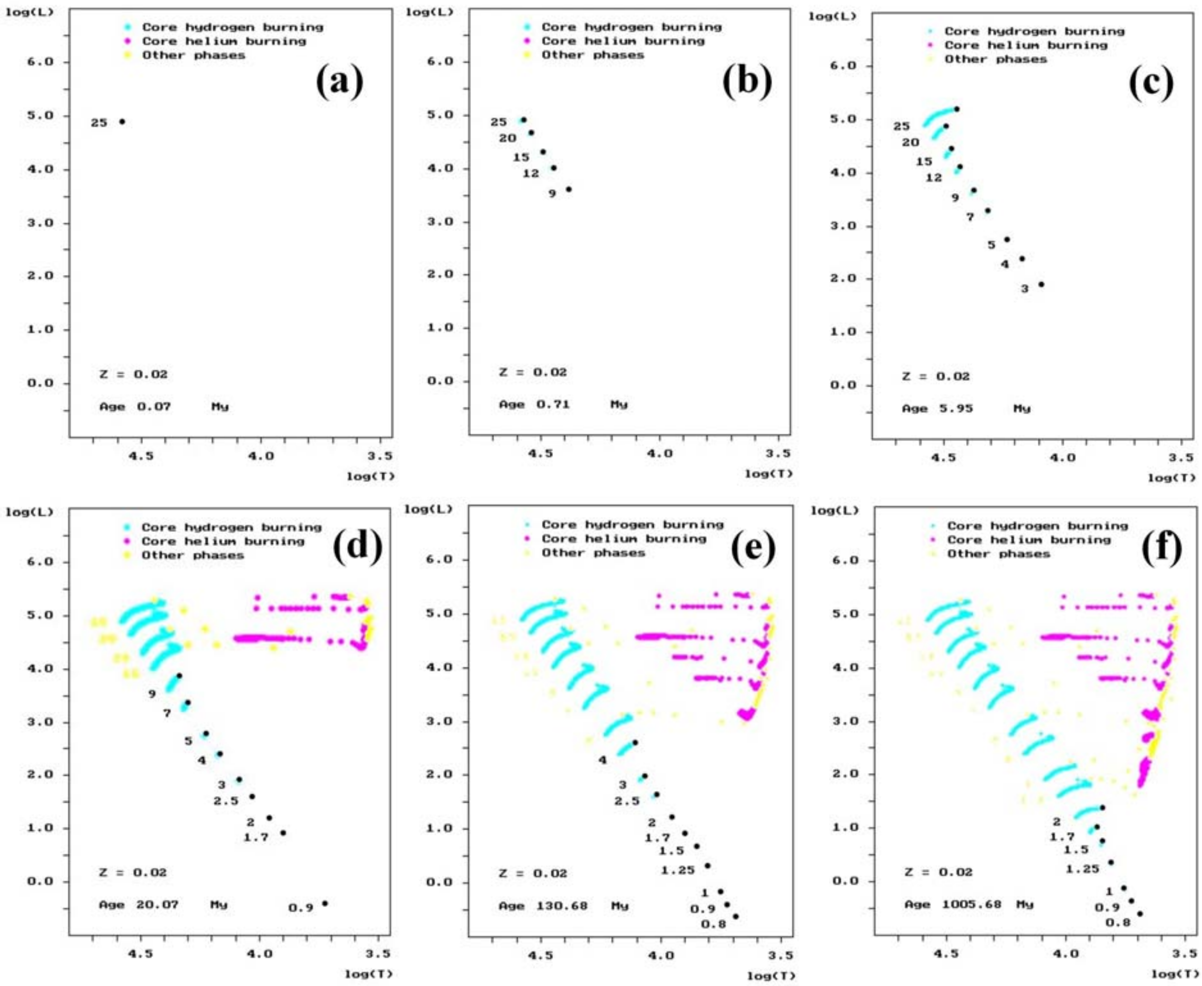

Figure 3. Simulation of stellar evolution as a function of time in the Log(L) vs. Log(T) (Hertzprung-Russell) diagram. The numbers near each initially black dot represent the stellar masses in M☉ units. The numbers in yellow represent stars that have reached the end of their cycle.

Interestingly, the above-mentioned circular features are little likely to survive new collisions as shown in Figure 4, which simulates the interaction of an elliptical galaxy with an idealised one having several concentric structures. The outer circular structures are strongly affected by the collision event, and after the collision only a few inner ones can still be observed, which will most likely be destroyed in a further such encounter. In contrast, some circular features appear in the elliptical galaxy following the collision. However, irrespective of the formation of tidal tails in an intermediate phase, after multiple galactic collisions one expects a gradual growth in importance of the galactic centre to finally produce elliptical galaxies.

In Figure 4 one can clearly see the ejection of material after the collision event. Some of this material may be recaptured by one of the two galaxies (see red arrow in Figure 4v), but some might escape the gravitational field. See yellow arrows in Figure 4vii for some candidate mass parcels that could possibly escape. If these escaping structures become self-gravitating, they might end up in dwarf tidal galaxies [2].

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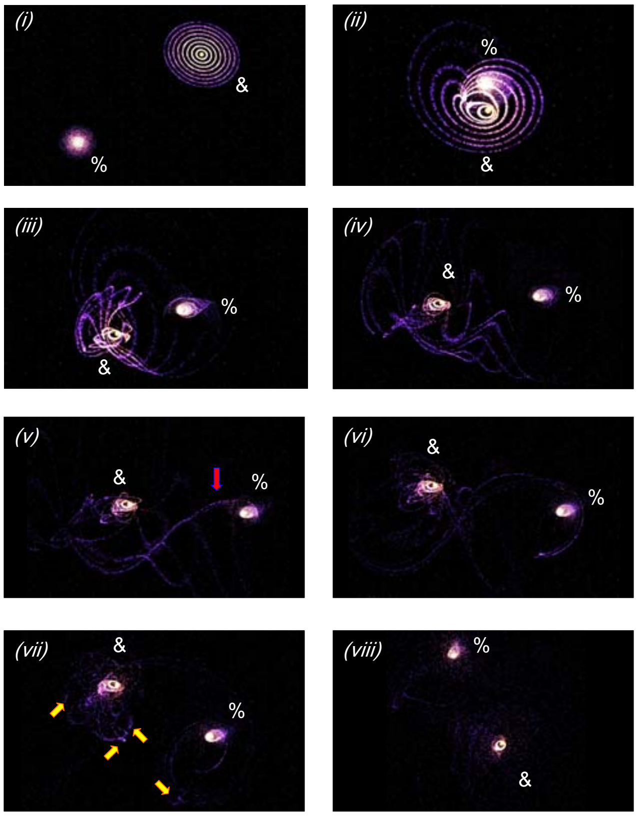

Figure 4. Simulated collision between two galaxies of equal mass (1010 M☉). Galaxy "%" is elliptical, while "&" shows several circular features of the kind that can be produced in a previous collision event (see e.g. Figure 2). The red arrow (red arrow in panel v) highlights material that is being gravitationally recaptured by the elliptical galaxy after the collision. The yellow arrows (yellow arrows in panel vii) represent long tidal tails that might escape the gravitational attraction of both the galaxies. Therefore, they are potential dwarf tidal galaxy candidates.

The mass and relative velocity of colliding galaxies are important parameters that can influence the outcome of galactic collisions. The effect of a collision on galactic morphology is higher if the initial relative velocity of the galaxies is lower. Figures 5 and 6 report the comparison between collisions of spiral galaxies of equal mass, with the initial relative velocity that is 50 times lower in the case of Figure 6 compared to Figure 5 (note that in both cases the velocity vectors still point in the same directions). It is evident that the low-velocity collision produces the highest modifications, most likely because a lower initial velocity causes a longer contact time with enhanced possibility for the collision-induced shock waves to operate changes in the galactic structure. The structures reported and highlighted in Figure 6(iii) are quite interesting because they can be defined as a stream and an inter-galactic bridge induced by the collision event. It should be highlighted that very similar structures have been observed in the case of the Magellanic clouds [18] that are known to have suffered a series of close encounters, the last ones taking place respectively 1.5 and 0.2 Gyr ago [21].

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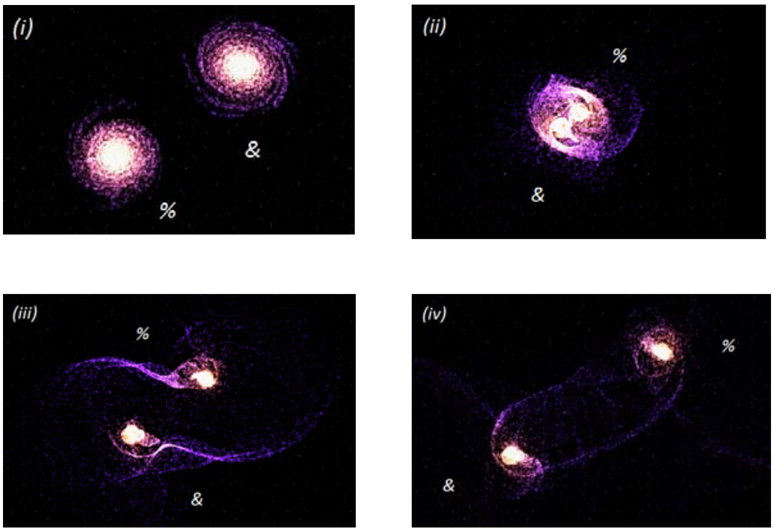

Figure 5. Simulated collision between two Sa galaxies of equal mass (1010 M☉).

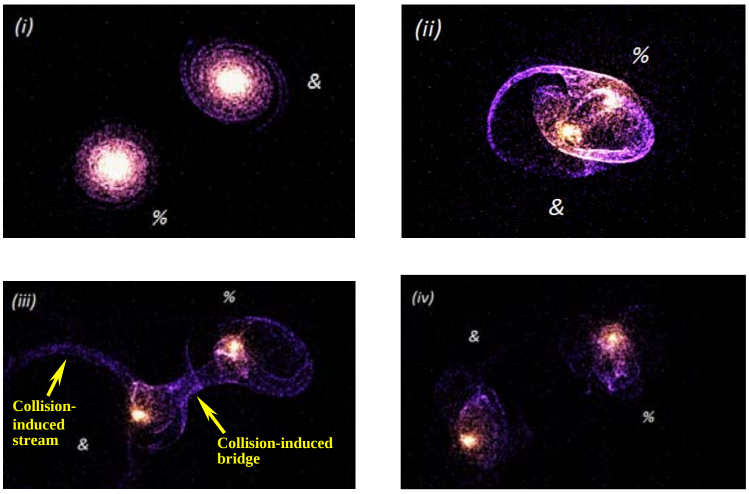

Figure 6. Simulated collision between two Sa galaxies of equal mass (1010 M☉). Conditions are the same as for Figure 5, except that here all components of the velocity vector were 50 times lower (for the "%" galaxy, vx = -1.7 km s–1, vy = 1.5 km s–1, vz = 0.1 km s–1; for the "&" galaxy, vx = -1.5 km s–1, vy = -0.5 km s–1, vz = -0.6 km s–1).

When a low-velocity collision involves massive galaxies, as shown in Figure 7, the reciprocal gravitational interaction may be sufficiently high to trap the two galaxies and induce multiple collisions, causing deep morphological modifications that finally induce the formation of compact objects. When galaxies of different mass collide, morphological changes may be substantial but the higher-mass galaxy succeeds to maintain a larger fraction of material around its centre. An example is shown in Figure 8 (collision between two Sb galaxies of different mass), where material from the spiral arms is recovered around the centre of the larger galaxy. In contrast, the smaller galaxy is almost totally stripped of spiral-arms matter after the collision. In this case, the bigger galaxy would strip matter from the smaller one. The phenomenon of inter-stellar gas stripping from a galaxy involves the interplay between the collision-induced pressure P_r and the gravitational restoring force F_r, and stripping occurring if P_r exceeds F_r [2,22]:

$$P_r \approx \rho_{ISM} v^2 > F_r = 2\pi G \Sigma_S \Sigma_{ISM} \quad \Rightarrow \quad \Sigma_S \Sigma_{ISM} < \frac{\rho_{ISM} v^2}{2\pi G} \tag{1}$$

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where ρ_{ISM} is the density of the inter-stellar medium (ISM), and v is the relative velocity of the colliding galaxies. Moreover, G is the constant of gravity, Σ_S the surface density of stars, and Σ_{ISM} the surface density of the inter-stellar medium (ISM). The relationship gives the value of the product $\Sigma_S\Sigma_{ISM}$, below which the phenomenon of gas stripping becomes possible. In the case of a collision with given relative velocity and with equal ρ_{ISM}, the higher values of Σ_S Σ_{ISM} in the larger galaxy ensure that it is the smaller galaxy that loses most of its mass, which can be partly recaptured by the more massive galaxy. The smaller galaxy is able to keep its central nucleus because the product $\Sigma_S\Sigma_{ISM}$ is larger there. This issue explains why a high-mass galaxy is predicted to be larger after collision with a smaller galaxy than after collision with a galaxy of equal mass (look for instance at the "&" galaxy in Figure 8 and Figure 9, respectively).

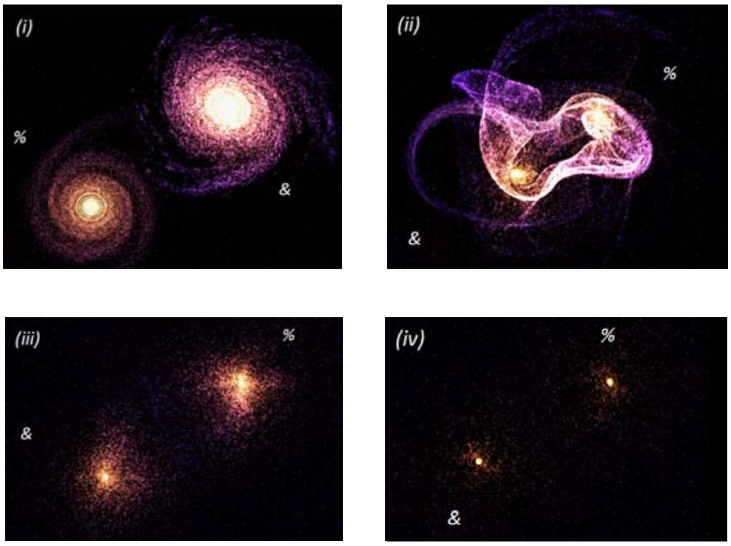

Figure 7. Simulated collision between two Sb galaxies of equal mass (5 · 1010 M⊙). The velocity vector was the same as per Figure 6 (for the “%” galaxy, vx = -1.7 km s–1, vy = 1.5 km s–1, vz = 0.1 km s–1; for the “&” galaxy, vx = -1.5 km s–1, vy = -0.5 km s–1, vz = -0.6 km s–1).

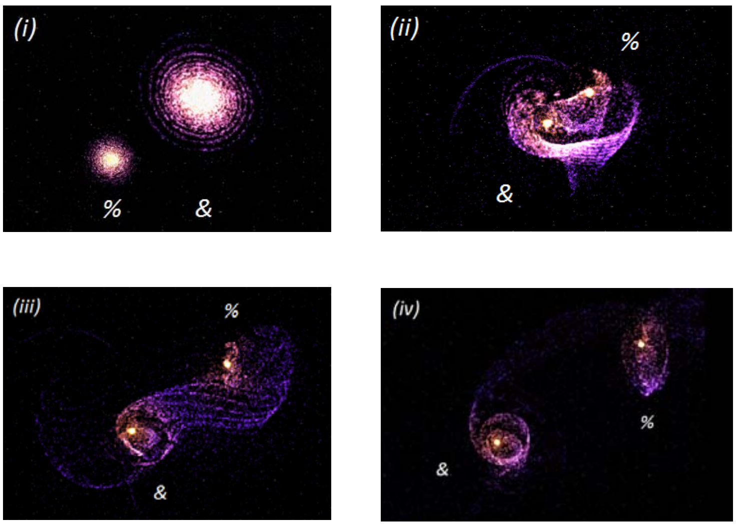

Figure 8. Simulated collision between two Sb galaxies (“%”: 109 M⊙; “&”: 1010 M⊙, default velocity vector).

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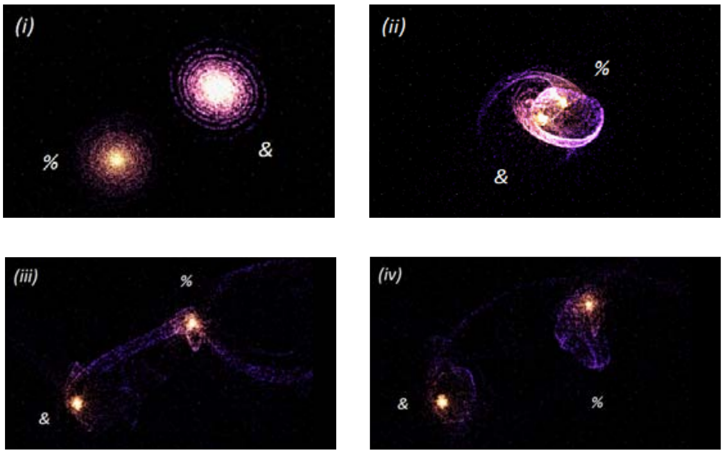

Figure 9. Simulated collision between two Sb galaxies of equal mass (1010 M☉, default velocity vector).

4 Conclusions

Relatively high-velocity galactic collisions, although not ending up in mergers, may deeply alter the morphology of the involved galaxies. Collisions involving spiral galaxies cause a change in mass and star distribution where the central nucleus acquires importance at the expense of the spiral arms. The same events can produce tidal waves, which either become self-gravitating or form pseudo-circular structures gravitating around the parent galaxy. The bright ~circular structures are likely the consequence of compression waves that increase the local density of both the existing stars and the inter-stellar gas. The latter effect triggers a massive star formation event that induces a further increase in brightness, at least for some My. However, our simulations show that circular structures are unlikely to survive a second collision, thereby allowing us to infer that the outcome of multiple collisions should be the formation of galaxies with an important central nucleus and absence of arms, irrespective of their initial morphology. Multiple collision events can involve a couple of galaxies provided that they have low enough relative velocity (and/or high enough masses) so as to remain gravitationally bound after the interaction. In this case, deep morphological changes are expected to occur and they finally produce objects having compact centres and no spiral arms.

When two galaxies of different mass collide, the larger one can more easily keep the mass perturbed by the collision within its own gravitational field. Indeed, the larger galaxy strips material from the smaller one that loses most of the mass surrounding its central nucleus. Among the collision-induced structures, we were able to reproduce streams and inter-galactic bridges observed for instance in interacting galaxies such as the Magellanic Clouds, which have undergone close encounters about 1.5 and 0.2 Gyr ago. Based on the results of this preliminary work, further research will reproduce further collision-induced structures by using reasonable parameters for the interacting galaxies.

References

1. B. Moore, in Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution (eds. J. S. Mulchaey, A. Dressler and A. Oemler), CUP, 2003.
2. J. Palous, Rev. Modern Astron. 18, 125, 2005.
3. B. Jungwiert, F. Combes and J. Palous, Astron. Astrophys. 376, 85, 2001.
4. G. Schaller, D. Schaerer, G. Meynet and A. Maeder, Astron. Astrophys. Suppl. Ser. 96, 269, 1992.
5. A. Chitre and C. J. Jog, Astron. Astrophys. 388, 407, 2002.
6. M. Bertschik and A. Burkert, Rev. Mex. Astron. Astrophys. 17, 144, 2003.
7. T. Naab and A. Burkert, Astrophys. J. 597, 893, 2003.
8. L. Gao, A. Loeb, P. J. E. Peebles, S. D. M. White and A. Jenkins, Astrophys. J. 614, 17, 2004.
9. Y. Li, M. M. MacLow and R. S. Klessen, Astrophys. J. L29, 2004.

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10.P. Amram, C. Mendes de Oliveira, H. Plana, C. Balkowski, C. Hernandez, C. Carignan,E. S. Cypriano, L. Sodré Jr., J. L. Gach and J. Boulsteix, Astrophys. J. 612, L5, 2004.
11.F. Bournaud, F. Combes and J. Jog, Astron. Astrophys. 418, L27, 2004.
12.L. M. Buson, F. Bertola, A. Bressan, D. Burstein and M. Cappellari, Astron. Astrophys. 423, 965, 2004.
13.P. A. Duc, E. Brinks and V. Springel, Astron. J. 10, 1238, 2000.
14.P. A. Duc, F. Bournaud and F. Masset, Astron. Astrophys. 427, 803, 2004.
15.S. Kim, L. Staveley-Smith, M. A. Dopita, K. C. Freeman, R. J. Sault, M. J. Kesteven and D. McConnell, Astrophys. J. 503, 674, 1998.
16.S. Kim, M. A. Dopita, L. Staveley-Smith and M. Bessel, Astron. J. 118, 2797, 1999.
17.E. Muller, L. Staveley-Smith, W. Zealey and S. Stanimirovic, Month. Not. Roy. Astron. Soc. 339, 105, 2003.
18.C. Bruns, J. Kerp, L. Staveley-Smith, U. Mebold, M. E. Putman, R. F. Haynes, P. M. W. Kalberla and E. Muller, Astron. Astrophys. 432, 45, 2005.
19.Gzwo Software Development, http://www.colliding-galaxies.com, last accessed October 2016.
20.L. Ondra, StarClock: Stellar evolution at PC. http://leo.astronomy.cz/sclock, last accessed October 2016.
21.L. T. Gardiner and M. Noguchi, Month. Not. Roy. Astron. Soc. 278, 191, 1996.
22.J. E. Gunn and J. R. Gott III, Astrophys. J. 176, 1, 1972.

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