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On the influence of ram-pressure stripping on interacting galaxies in clusters

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ABSTRACT

We investigate the influence of ram pressure on the star-formation rate and the distribution of gas and stellar matter in interacting model galaxies in clusters. To simulate the baryonic and non-baryonic components of interacting disc galaxies moving through a hot, thin medium, we use a combined N -body/hydrodynamic code GADGET2 with a description for star formation based on density thresholds. Two identical model spiral galaxies on a collision trajectory with three different configurations were investigated in detail. In the first configuration, the galaxies collide without the presence of an ambient medium. In the second configurations, the ram pressure acts face-on on the interacting galaxies and in the third configuration the ram pressure acts edge-on. The ambient medium is thin ($10^{-28} \text{ g cm}^{-3}$), hot ($3 \text{ keV} \approx 3.6 \times 10^7 \text{ K}$) and has a relative velocity of 1000 km s^{-1} , to mimic an average low ram pressure in the outskirts of galaxy clusters. The interaction velocities are comparable to galaxy interactions in groups, falling along filaments into galaxy clusters. The global star-formation rate of the interacting system is enhanced in the presence of ram pressure by a factor of 3 in comparison to the same interaction without the presence of an ambient medium. The tidal tails and the gaseous bridge of the interacting system are almost completely destroyed by the ram pressure. The amount of gas in the wake of the interacting system is ~ 50 per cent of the total gas of the colliding galaxies after 500 Myr the galaxies start to feel the ram pressure. Nearly ~ 10 – 15 per cent in mass of all newly formed stars are formed in the wake of the interacting system at distances larger than 20 kpc behind the stellar discs. As the tidal tails and the gaseous bridge between the interacting systems feel the ram pressure, knots of cold gas ($T < 1 \times 10^5 \text{ K}$) start to form. These irregular structures contain several $10^6 M_{\odot}$ of cold gas and newly formed stars and, as the ram pressure acts on them, they move far away (several 100 kpc) from the stellar discs. They can be classified as ‘stripped baryonic dwarf’ galaxies. These ‘stripped baryonic dwarfs’ are strongly affected by turbulence, for example Kelvin–Helmholtz instabilities, which are not resolvable within the presented smoothed particle hydrodynamics simulations. Heat conduction, which is not included, would affect these small structures as well. Therefore, we give some estimate on the lifetime of these objects.

Key words: hydrodynamics – methods: numerical – galaxies: interactions – intergalactic medium – galaxies: stellar content – galaxies: structure.

1 INTRODUCTION

Multiwavelength observations have shown that the star-formation rate in interacting galaxies is enhanced in comparison to isolated galaxies (Sulentic 1976; Stocke 1978; Bushouse 1987; Solomon & Sage 1988; Combes et al. 1994; Kewley, Geller & Barton 2006, and

references therein). To understand the physical processes involved in interacting galaxies, numerical simulations are an ideal tool. Since, the first publications in this field (Pfleiderer 1963; Toomre & Toomre 1972) it is evident that interactions are the sources of tidal tails, bridges and other signs of massive perturbations in and around the discs of galaxies. First calculations including star formation and gas depletion in interacting systems (e.g. Noguchi & Ishibashi 1986; Olson & Kwan 1990a,b; Noguchi 1991; Mihos, Richstone & Bothun 1992; Mihos & Hernquist 1996) indicated that galaxy

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mergers are able to increase the total star formation of the system up to an order of magnitude and that these events of strong starbursts are able to deplete the cold-gas reservoir of the system significantly. Many numerical investigations put special emphasis on modelling observed interacting systems, like NGC7252 (Mihos, Dubinski & Hernquist 1998) or on the dependence of the star-formation rates on interaction parameters like spatial alignment and minimum separation (di Matteo et al. 2007; Kapferer et al. 2005). Bournaud, Jog & Combes (2005) investigated the remnants of galaxy mergers with different mass ratios; Mayer et al. (2006) showed via numerical simulations that dwarf galaxies lose their gas by ram pressure and tidal stripping during passages through a disc. Cox et al. (2004) investigated galaxy mergers with special emphasis on the heating process of gas due to shocks. The formation of dwarf galaxies in the debris of interacting galaxies was investigated by Duc, Bournaud & Masset (2004). The accretion on to supermassive black holes in merging galaxies and the resulting suppression of star formation and the morphology of the elliptical remnants were investigated by Springel, Di Matteo & Hernquist (2005a,b).

From observations of the Virgo cluster of galaxies, it is reported that galaxies moving through a galaxy cluster suffer mass-loss gas by the ram pressure of the intracluster medium (ICM) on to the interstellar medium (ISM) (Gunn & Gott 1972; Cayatte et al. 1990; Kenney, van Gorkom & Vollmer 2004; Vollmer et al. 2004). To study the effects of ram-pressure stripping in detail, several numerical approaches were carried out, from very simple descriptions for the gas phase, like sticky particles (e.g. Vollmer et al. 2001), to advanced Eulerian grid techniques (e.g. Roediger & Brüggén 2006) or Lagrangian descriptions of hydrodynamics (e.g. Schulz & Struck 2001; Jáchym et al. 2007), so called smoothed particle hydrodynamics (SPH). All these methods were applied to single model disc galaxies interacting with a time dependent or a constant pressure from a hot gas phase outside the disc. Recently, the investigation of the dependence of ram pressure on the star formation of a single model galaxy moving through an ambient medium was done by Kronberger et al. (2008).

On larger scales the effect of ram-pressure stripping on the chemical enrichment was studied in cosmological galaxy-cluster simulations. To model the physics involved below the resolution of such simulations an analytical approach for the mass loss by ram-pressure stripping was introduced, based on the Gunn & Gott criterion (Schindler et al. 2005; Domainko et al. 2006). In combination with the mass losses by galactic winds and starbursts, ram-pressure stripping is able to enrich the ICM to observed levels (Kapferer et al. 2007).

In this paper, we concentrate on the distribution of baryonic, stellar and gaseous matter, in interacting disc galaxies moving through an ambient hot medium. By applying a density threshold technique to model star formation (Springel & Hernquist 2003), we present the impact of ram-pressure stripping on the star-formation rate and the positions of star formation in comparison to galaxy interactions without the presence of ram pressure.

2 THE SIMULATION SETUP

2.1 The initial model for the model galaxies

The model galaxies were created with an initial disc galaxy generator developed by Volker Springel. Details and analysis can be found in Springel et al. (2005a). The total mass and the virial radius of the

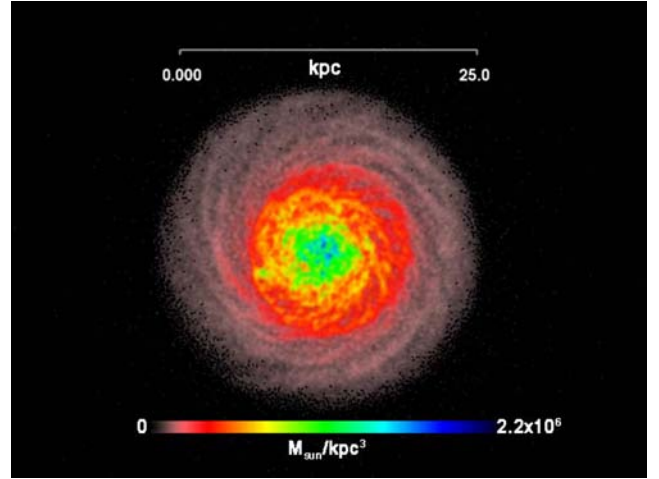


Figure 1. The gas distribution in the disc of the model galaxy after 2 Gyr of evolution without ram pressure and interaction seen face-on.

galaxies' halo are given by

$$M_{200} = \frac{v_{200}^3}{10 G H(z)} \quad \text{and} \quad r_{200} = \frac{v_{200}}{10 H(z)}, \quad (1)$$

with $H(z)$ the Hubble constant at redshift z and G the gravitational constant. We constructed a model galaxy with a disc-scale length of 3.3 kpc and a circular velocity of the halo of 160 km s^{-1} . The gas fraction in the disc is initially 25 per cent of the total disc mass. The mass resolution of the different components of the galaxies (gas, stellar, dark matter) can be found in Section 2.4. In Fig. 1, the gas distribution of the model galaxy after 2 Gyr of evolution without ram pressure and interaction is shown.

2.2 The star formation and feedback model

We applied the so-called hybrid method for star formation and feedback introduced by Springel & Hernquist (2003). The basic assumption of this model is the conversion of cold clouds into stars on a characteristic time-scale t_* and the release of a certain mass fraction β due to supernovae (SNe). The relation can be expressed as

$$\frac{d\rho_*}{dt} = \frac{\rho_c}{t_*} - \beta \frac{\rho_c}{t_*} = (1 - \beta) \frac{\rho_c}{t_*}, \quad (2)$$

where ρ_* and ρ_c are the stellar and cold gas phase densities, respectively. The factor β gives the mass fraction of stars above $8 M_\odot$, which is in our simulations 0.1, adopting a Salpeter initial mass function with a slope of -1.35 in the mass interval $0.1\text{--}40 M_\odot$. Each SN explosion heats the surrounding gas in the bubble leading to an evaporation of cold gas. The minimum-temperature gas can reach due to radiative cooling is 10^4 K . From observations and analytical models, it is evident that a certain fraction of matter can escape the galaxies potential due to thermal and or cosmic-ray driven winds due to SN explosions (Breitschwerdt, McKenzie & Völk 1991). This decreases the mass and energy budget of a galaxy, especially in the case of starbursts. To take this into account, we applied the same method as Springel & Hernquist (2003) and scale the mass outflow in such a way, that the mass outflow is proportional to the star-formation rate of the underlying system, with a proportionally factor of 2. Following the mass budget for the hot and cold gas due to star formation, mass feedback, cloud evaporation, growth of clouds due to radiative cooling and mass outflow by

a galactic wind lead to a selfconsistent description of star formation in disc galaxies. More details on the model can be found in Springel & Hernquist (2003).

2.3 The merger and the ram pressure

To study galaxy–galaxy interactions in an ICM wind, we place the two model galaxies on Keplerian orbits (see Duc et al. 2000 for details) with a maximum separation of 200 kpc, a minimum separation of 1 kpc and oriented edge-on, after they have evolved for 2 Gyr without any interaction. The relative velocity of the encounter is $\sim 300 \text{ km s}^{-1}$, which makes the studied merger comparable to galaxy mergers within groups, falling along filaments into galaxy clusters. After 2 Gyr of evolution, the spiral structure of the disc galaxies is evolved. In addition to the interaction trajectory, we gave the whole system a directed velocity of 1000 km s^{-1} through a hot ($3.6 \times 10^7 \text{ K}$) and thin ($10^{-28} \text{ g cm}^{-3}$) medium. This is done in two different configurations. In the first configuration, the galaxies fly face-on through the ICM, and in the second configuration, edge-on while they interact with each other, see Fig. 2. To compare the effects of the ram pressure, we calculate as a third configuration of the same galaxy interaction without an ambient medium. The galaxies collide always edge-on. The simulation of the ram pressure on the interacting galaxy pair was carried out for 1 Gyr, so that the system has a first encounter but has not merged yet.

To study the influence of ram pressure by an ambient medium on the distribution of the tidal tails, the gaseous bridges and the star-formation rates, we let the interaction take place in a homogeneous density and a constant temperature distribution of the ambient medium. Therefore, the effects of ram-pressure stripping are accessible. The influence of a varying ICM temperature and density distributions will be investigated in an upcoming work.

2.4 The resolution

The influence of the resolution on the global star-formation rate of interacting galaxies was investigated in Kapferer et al. (2005). It was found that for interacting disc galaxies the global star formation does not vary for mass resolutions below $10^6 M_\odot$ for the stellar and gas particles in the disc. To resolve star-forming regions, in the bridges and tidal tails a higher resolution was adopted in the present

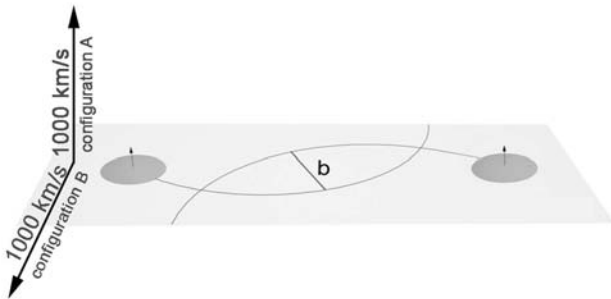


Figure 2. Interaction geometry and the two configurations. The galaxies’ positions and velocities are chosen such that the galaxies are point masses moving on Keplerian orbits. See Duc et al. (2000) for further descriptions. In configuration A the galaxies move with 1000 km s^{-1} face-on through the hot ambient medium, whereas configuration B represents the edge-on flight through the medium. Between the configurations is an angle of 90° . Configuration C (not imprinted) is the same encounter without an ambient medium acting on it.

Table 1. Initial properties of one model galaxy and the ICM.

	Number of particles	Mass resolution [M_\odot /particle]	Total mass [M_\odot]
DM halo	3×10^5	3.5×10^6	1.05×10^{12}
Gaseous disc	2×10^5	3.4×10^4	6.8×10^9
Stellar disc	2×10^5	1×10^5	2×10^{10}
ICM	1×10^6	1.46×10^6	1.5×10^{12}
ICM hr ¹	1×10^7	1.46×10^5	1.5×10^{12}

¹High resolution.

simulations. The total mass of the model galaxy is $1.09 \times 10^{12} M_\odot$, the disc mass is $2.7 \times 10^{10} M_\odot$ with a 25 per cent gas content. We assigned 7×10^5 particles to each model galaxy. In Table 1, the particle numbers and corresponding mass resolutions for a single model galaxy and the ICM are listed. The ambient medium was sampled by 1×10^6 gas particles in a box with 1 Mpc on a side. To study the influence of a higher resolved ambient medium, we performed a simulation with 10 times more gas particles. The star-formation rate and the distribution of the gaseous matter did not change significantly. The same trend for the star-formation rate is present in the high- and the low-resolution simulation, see Fig. 3. The mean smoothing length for ISM gas particles in our simulations is 0.978 kpc and the mean smoothing length for ICM particles is 1.17 kpc. The gravitational softening for gas particles is 0.03 kpc, for halo particles 0.02 kpc and for collisionless disc particles 0.05 kpc.

2.5 Kelvin–Helmholtz instabilities and thermal conductivity

Kelvin–Helmholtz instabilities develop in the case of a velocity shear within a fluid or when there is a velocity difference along the interface between two fluids. To resolve and treat this kind of turbulent behaviour in hydrodynamics is a challenge. A comprehensive analysis of the treatment of Kelvin–Helmholtz instabilities and other turbulent phenomena, such as Rayleigh–Taylor instabilities, was carried out with two commonly used techniques, namely Eulerian grid based and SPH by Agertz et al. (2007). They conclude in their comparison that grid codes are able to resolve and

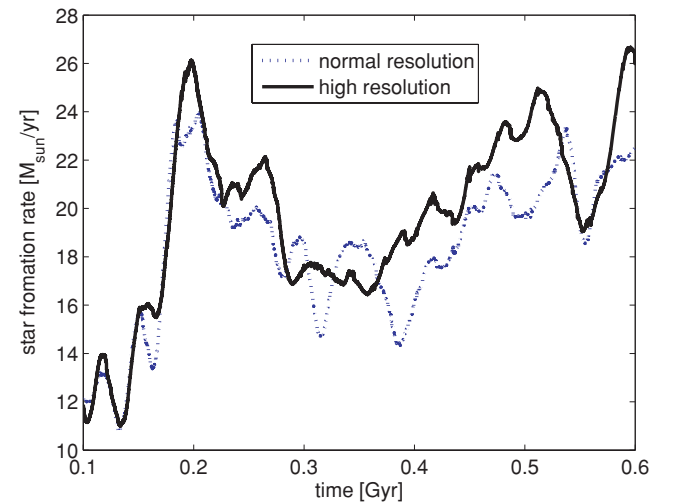


Figure 3. The star-formation rates for two interacting galaxies moving edge-on through the ambient medium as a function of time. The same trend in the normal resolution and high resolution simulation is present.

treat dynamical instabilities and mixing, while SPH codes are not. According to Agertz et al. (2007), the reason for this is that SPH has severe problems in the case of strong density gradients. SPH particles representing low-density regions near to high-density regions are decoupled by erroneous pressure force calculations due to the asymmetric density within the symmetric smoothing kernel. This leads to a decoupling in the different phases of the fluid, leading to an artificial suppression in the growth of turbulent structures, such as Kelvin–Helmholtz instabilities. In addition, Agertz et al. (2007) conclude that for time-scales below the typical dynamical time-scales of the turbulent structure, SPH and Eulerian grid-based schemes agree.

In McCarthy et al. (2008), the stripping of a hot gaseous matter around galaxies in groups and clusters was investigated by applying the SPH scheme. They give an estimate for the Kelvin–Helmholtz time-scale (equation 4, McCarthy et al. 2007), based on the work of Mori & Burkert (2000) (equation 22). It is important to note that these estimates are in principle only applicable for spherical distributions and a particular relation between the galaxy core radius and mass. Dropping the relation between the galaxy core radius and mass and assuming that asphericity only introduces a modest change, this leads to time-scales in the range of Gyr for the main galaxies. As we stop our simulation after 1 Gyr, we conclude that although Kelvin–Helmholtz instabilities are not well resolved in SPH simulations our results regarding the main galaxies are not strongly affected by it. For the small clumps, the situation is different. Here, the Kelvin–Helmholtz instabilities are in the range of several 100 Myr, assuming a relative velocity of 1000 km s^{-1} and the low density of the ICM. Therefore, the gas clumps can be stripped completely. Many of these clumps from gas which originates from gas stripped into the slip stream of the galaxies. In this situation, the structures are not affected by the ram pressure as strongly as in other regions. When entering the ICM wind the clumps will be decelerated to several 100 km s^{-1} relative velocities. This leads to longer Kelvin–Helmholtz time-scales. Another issue not addressed in the simulation is heat conduction, which should in principle heat the gaseous clumps and therefore prevent them from becoming denser, therefore altering the star-formation efficiency. The evaporation time-scale due to thermal conductivity of a gas clump with a n_H column density of 50 cm^{-3} and a size of 1 kpc (assuming spherical geometry) in an ambient $3.6 \times 10^7 \text{ K}$ gas with an electron number density of 10^{-1} is in the range of 500 Myr, according to Nipoti & Binney (2007). In the case of the ICM electron number densities, which are two orders of magnitudes smaller, these evaporation times would be even larger. Note that, the simulations presented in this work are a simplified step towards the understanding of the complex physics involved in environmental effects in the evolution of galaxies. The multiphase multiscale gas physics, together with magnetic fields involved in star formation, require complex and fully consistent theoretical models which are not achieved yet.

3 RESULTS

3.1 The distribution of the different components

The most striking difference between galaxy–galaxy interactions, suffering or not from ram pressure is the evolution of the distribution of the gaseous tidal tails and the gas bridge between the interacting galaxies. In Fig. 4, the gas distribution for the interacting model galaxies is shown at the apocentre of the interaction. In the upper panel, the galaxies interact without the ram pressure acting on them,

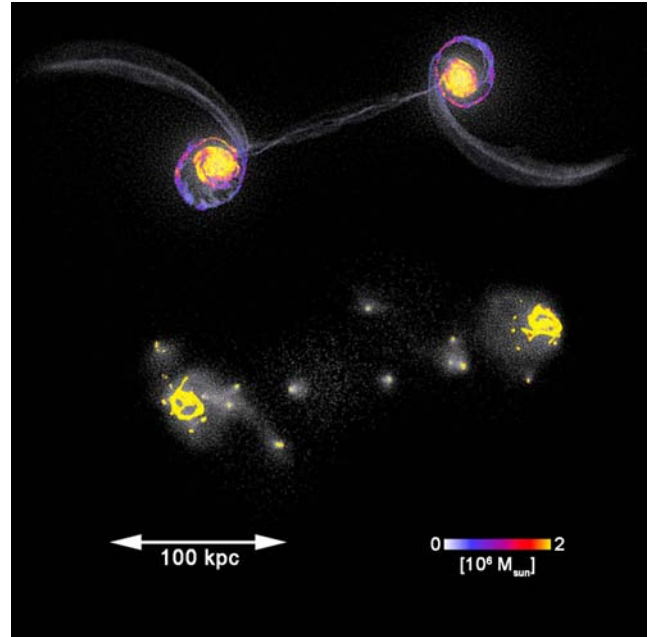


Figure 4. The gas density of the interacting galaxies seen face-on. In the lower panel the interaction takes place in an ambient medium with a constant ram pressure acting face-on at the system, whereas in the upper panel no ambient gas is present.

whereas in the lower panel the effect of the ram pressure is shown. As the galaxies move face-on through the ICM, the gas feels the pressure of the ambient medium, resulting in an increasing offset of the stripped gas, especially at the tidal tails and the bridge. The gaseous bridge between the galaxies and parts of the tidal tails are compressed and fragmented into massive ($\sim 10^6 M_{\odot}$) gas clumps, which cool due to radiation and form new stars. In Fig. 5, the stellar density of the interacting galaxies seen face-on is shown. In the lower panel, the interaction takes place in an ambient medium with a constant ram pressure acting face-on at the system, whereas in the upper panel no ambient gas is present. The new-formed stars are coloured blue, whereas the old stellar population is coloured yellow. In Fig. 6, the fraction of stripped gas to the total amount of gas in the wake (distance larger than 20 kpc from the stellar disc) is shown for an interacting system moving face-on through the ambient medium as a function of time. After 500 Myr, nearly 50 per cent of the gas in the interacting system is located 20 kpc behind the stellar discs of the system. In this gaseous, wake approximately 10 per cent of all new stars are formed after 500 Myr.

The evolution of the wake is presented in Fig. 7. The distribution of the gas in the interacting galaxies is shown at different timesteps. The left column shows the face-on and the right column the edge-on view. The interval of time between each row is 250 Myr. Panel (a) and (e) show the situation at the first encounter. The ram pressure already distorts the outer gas layers. The effect of the ram pressure on the tidal tails and bridges starts after the galaxies have had the first encounter. In panels (b) and (f), the compression of the gas is already distinct. As the gas gets more compressed, it cools and becomes denser. Parts of the cooled gas fall back on to the discs leading to episodes of star formation in the disc. In panels (c) and (g), the tidal tails and the gaseous bridge are nearly completely destroyed. Only dense knots are visible around the discs at distances larger than 50 kpc. The knots are star-forming regions with several $10^5 M_{\odot}$ of newly formed stars. The last timestep shows that the dense knots of

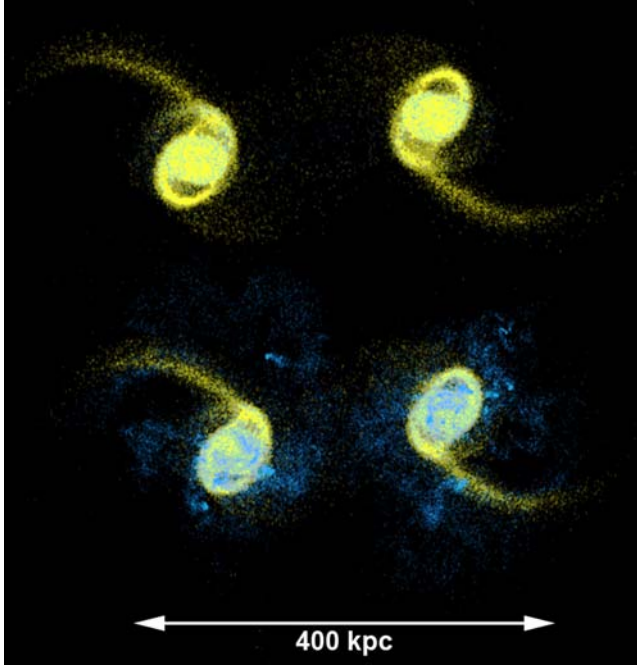


Figure 5. The stellar density of the interacting galaxies seen face-on. In the lower panel the interaction takes place in an ambient medium with a constant ram pressure acting face-on at the system, whereas in the upper panel no ambient gas is present. The new formed stars are coloured blue, whereas the old stellar population is coloured yellow.

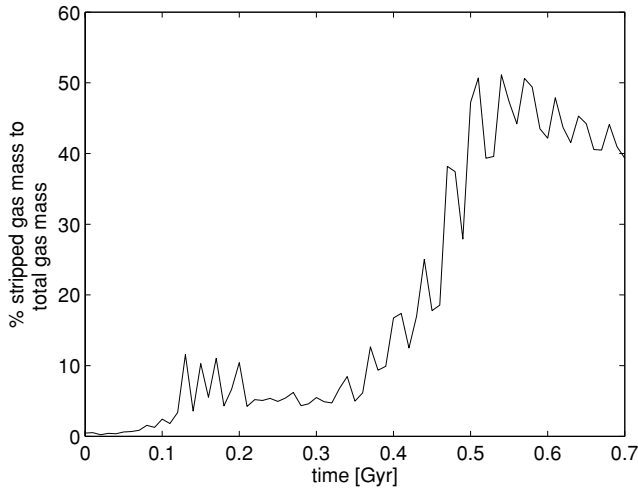


Figure 6. The amount of gas in the wake (distance to the stellar disc larger than 20 kpc) as fraction of the total amount of gas. In this model the galaxies are moving face-on through the ambient medium.

gas become more and more separated from the interacting system. While these knots form stars, more and more gas is transformed into stellar matter, leading to small irregular structures with several $10^6 M_{\odot}$ of baryonic matter.

The evolution of the ratio of heated gas ($T > 10^7$ K) in the wake originating from the interacting system to the total gas of the system is given in Fig. 8. After 0.7 Gyr, ~ 5 -6 per cent of the stripped material in the interacting system is heated to temperatures above $T > 10^7$ K. This gas will show its signatures in X-ray observations of the system.

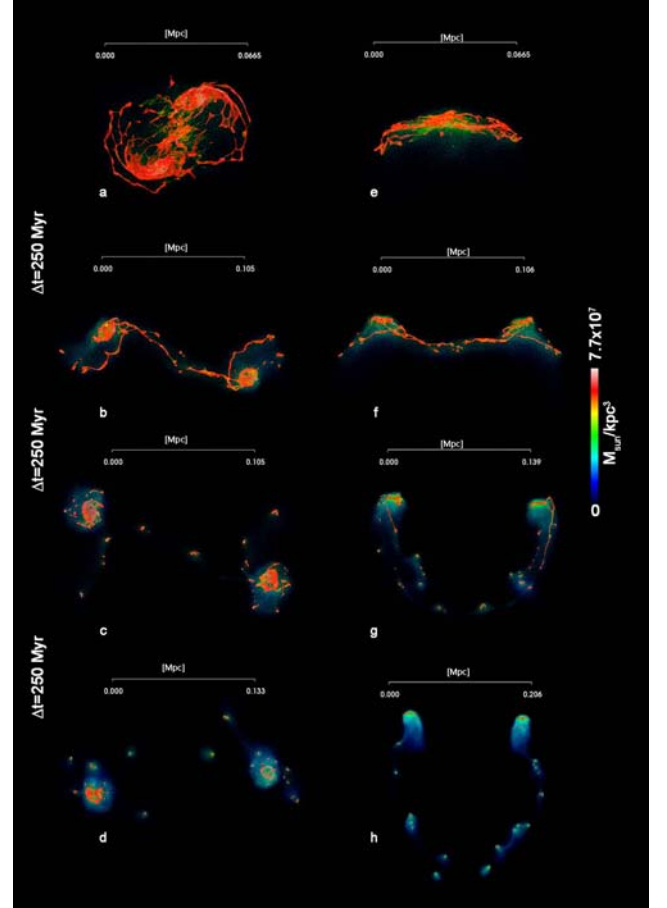


Figure 7. Distribution of gas in the interacting galaxy pair exposed to a constant ram pressure acting on the galaxies face-on, seen from different sides: left face-on, right edge-on. Between each row 250 Myr of evolution are present. The density of the ambient medium (not shown here) has a constant density of $10^{-28} \text{ g cm}^{-3}$ and a temperature of 3 keV. The relative velocity of the interacting pair to the ambient medium is 1000 km s^{-1} .

In the case of the galaxies moving edge-on through the ambient medium, the distribution of matter is very similar. The gaseous bridge and the tidal tails are destroyed by the ram pressure. Dense knots of gas form, which cool in the same way as in the face-on situation. The remaining gaseous discs are truncated very similarly as in the face-on passage. We have additionally investigated the robustness of our results with respect to the resolution. In Fig. 9, the distribution of gas of the interacting galaxies after 1 Gyr of evolution in the high-resolution ICM simulation (a) and normal resolution ICM simulation (b) are shown. In the highly resolved ICM simulation the knots of gas, which form from stripped matter in the gaseous bridges and the tidal tails are present as in the normal resolved ICM simulation. The calculated amount of gas in the wake, originating from the interacting galaxies, defined as gas which lacks 20 kpc behind the discs, is 48 per cent in the case of the highly resolved ICM simulation and 43 per cent in the normal resolved simulation. As the ram-pressure is the dominating mechanism, galactic outflows do not alter the mass distribution significantly. The amount of gaseous and stellar matter in the wake of the interacting galaxies is not changed.

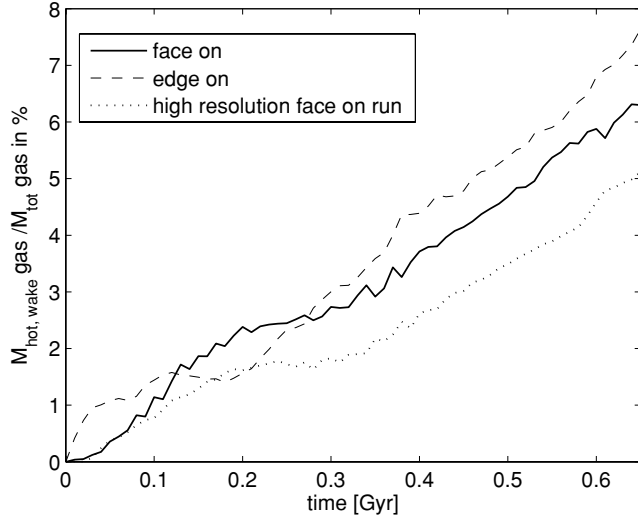


Figure 8. The amount of gas originating from the interacting galaxies in the wake (distance to the stellar disc larger than 20 kpc) and with temperatures $T > 1 \times 10^7$ K as fraction of the total amount of gas in the interacting system for three cases, face-on, edge-on and for the high resolution face-on simulation.

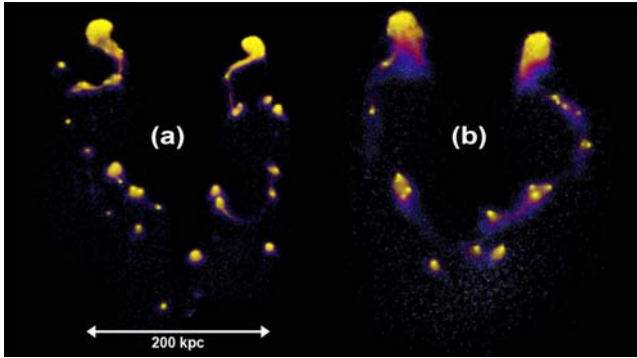


Figure 9. The distribution of gas in the interacting galaxies after 1 Gyr of evolution in the high resolution ICM simulation (a) and normal resolution ICM simulation (b), seen edge-on.

3.2 The star-formation rate and the regions of star formation

To study the effects of constant ram pressure on the star formation, we did as a first step simulations with a single disc galaxy moving through a hot medium with 1000 km s^{-1} relative velocity. The results of these investigations are discussed in detail in Kronberger et al. (2008). In the case of the interacting galaxies in an ambient medium, newly formed stars can be found up to 100 kpc behind the plane of the disc. In Fig. 10, the evolution of the ratio of newly formed stars in the wake to the total amount of newly formed stars in the case of the face-on interaction is shown. The definition for newly formed stars in the wake is a distance larger than 20 kpc to the interacting discs. Almost 20 per cent of all newly formed stars are located at a distance of more than 20 kpc to the interacting discs after a simulation time of roughly 1 Gyr. The evolution of the total star-formation rate for the interacting systems is shown in Fig. 11. In the case of the interaction without an ambient medium, the first encounter increases the star-formation rate by a factor of ~ 3 . After the first encounter, the global star-formation rate decreases to slightly smaller rates than before. This can be explained by the formation of the tidal tails and the bridge, which decrease the gas content of the discs.

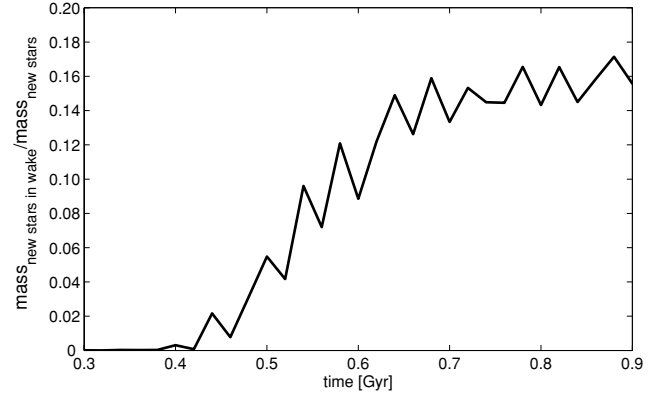


Figure 10. The evolution of the ratio of newly formed stars in the wake to the total amount of newly formed stars in the case of the face-on interaction. The definition for the stars in the wake is a distance larger than 20 kpc to the interacting discs.

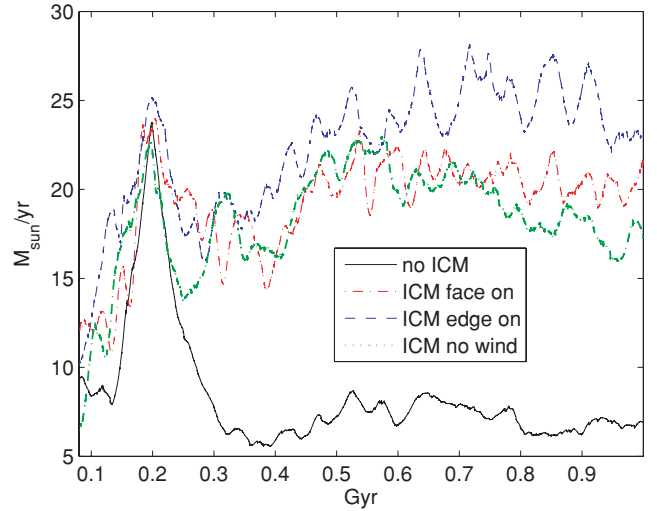


Figure 11. The star-formation rate of the merging system as a function of time for four different configurations. The black solid line shows the star-formation rate for the interacting system without ambient medium, the dashed blue line gives the face-on case of the ram pressure, the dotted red line the edge-on ram-pressure case, corresponding to configurations A and B in Fig. 1. The dotted green line gives the star-formation rate for an interaction taking place in the ambient medium without a constant wind.

In the case of an external ram pressure, the situation is very different. After the first encounter, the star-formation enhancement does not decrease. This different behaviour is present in both configurations, face-on and edge-on acting ram pressure. The reason for the enhancement can be found in the compression and deformation of the tidal tails and the gaseous bridges, as well as the compression of the discs due to the external pressure of the ICM on it. By comparing the star-formation rates with a simulation in the ICM with no directed wind reveals that most of the enhancement belongs to the pressure of the ICM on to the galaxies. As the bridges and the tails are affected in the same way in the case of face-on and edge-on ram pressure, the total star-formation rate does not vary significantly between the two configurations. The influence of the outflow of a galactic wind on the star-formation rate is minor. As the outflow is kept in the range of twice the star-formation rate, which is in agreement with observations (Martin 1999), it is a negligible mass loss of the interacting system in comparison to the

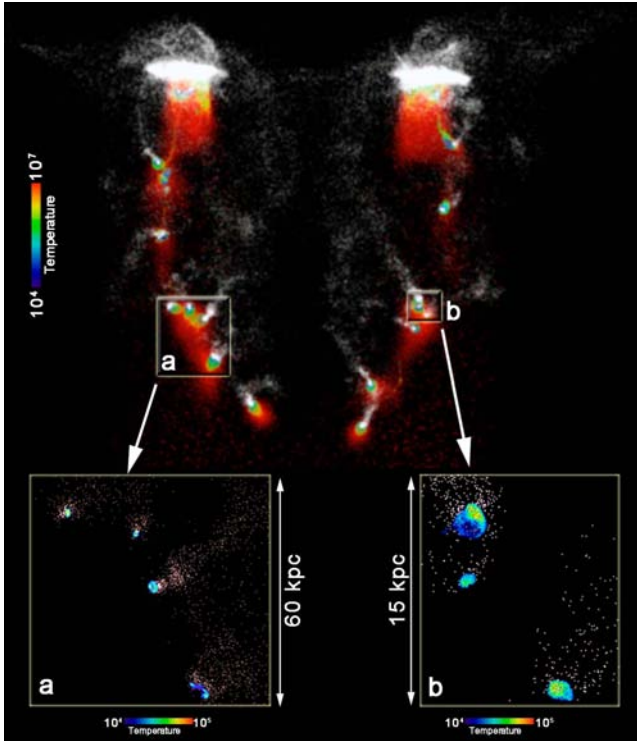


Figure 12. The gas and stellar distribution of matter in the wake of two interacting galaxies moving face-on through an ambient thin ($10^{-28} \text{ g cm}^{-3}$), hot ($5 \times 10^7 \text{ K}$) medium with 1000 km s^{-1} . The gaseous component of the wake is colour coded for the temperature, whereas the newly formed stars in the system are shown in white colour. The inserts (a) and (b) give two irregular structures in the wake of the interacting galaxies in more detail. Note that only the cold gas and newly formed stars are shown in the inserts. The total gas mass in insert (a) is $3.5 \times 10^6 M_{\odot}$, the total stellar mass present in the volume shown by insert (a) is $3.4 \times 10^6 M_{\odot}$. The total gas mass located in the region shown in insert (b) is $2.3 \times 10^6 M_{\odot}$ and the total stellar mass present in insert (b) is $5.9 \times 10^5 M_{\odot}$.

amount of stripped matter. The cool, dense knots and the distorted gas in the discs form new stars. In Fig. 12, the star-forming regions in the simulation of face-on ram pressure are shown. The upper panel shows an edge-on view of the interacting system with the temperature colour-coded gas distribution. Additionally, the newly formed stars are highlighted as white points. The lower panels give two star-forming regions (a) and (b) in a larger view. Only the cool gas ($T < 10^5 \text{ K}$) and newly formed stars are shown. The total gas mass, originating from the interacting system in insert (a) is $3.5 \times 10^6 M_{\odot}$, the total stellar mass present in the volume shown by insert (a) is $3.5 \times 10^6 M_{\odot}$. The total gas mass, stripped from the interacting system and presented in insert (b) is $2.3 \times 10^6 M_{\odot}$ and the total stellar mass present in insert (b) is $5.9 \times 10^5 M_{\odot}$.

4 COMPARISON TO OBSERVATIONS

As the merger investigated in this work is more likely happening in groups, located in the infall regions of galaxy cluster, a direct comparison to observations of mergers within galaxy clusters is restricted. Nevertheless some observations, especially those in the outskirts of galaxy clusters, can be compared to study the influence of a low ram pressure. Since, the first H I radio atlas of the Virgo cluster by Cayatte et al. (1990), it was found that ram-pressure stripping affects the star formation of cluster galaxies. Up to now,

X-ray observations revealed the existence of tails or wakes of gas, probably associated to ram-pressure stripping, in about 10 elliptical cluster galaxies or group galaxies (Kim et al. 2007; Jeltama, Binder & Mulchaey 2008 and Schindler & Diaferio 2008, and references therein). Only in recent years, optical radio and X-ray observations have started to accumulate evidence of gas tails stripped from late-type cluster galaxies at 100 kpc scales (e.g. UGC 6697, CGCG 97-073/97-079 in A1367: Gavazzi et al. 2001a,b; Sun & Vikhlinin 2005 – C153 in A2125: Wang, Owen & Ledlow 2004 – ESO 137-001 in A3627: Sun et al. 2006; Sun, Donahue & Voit 2007 – NGC 4525, NGC 4388 and NGC 4532/DDO 137 in Virgo: Yoshida et al. 2002; Oosterloo & van Gorkom 2005; Haynes, Giovanelli & Kent 2007; Koopmann 2007 – D100 in Coma: Yagi et al. 2007). Most of these galaxies show signatures of enhanced star formation. The fact that some of them are interacting objects is well proven (e.g. CGCG 97-073/97-079 in A1367: Gavazzi et al. 2001b, NGC 4532/DDO 137 in Virgo, Koopmann 2007), still debated in other cases (e.g. UGC 6697 in A1367, Gavazzi et al. 2001a, NGC 4254 in Virgo, Vollmer, Huchtmeier & van Driel 2005). Concerning this point, it is worth to be stressed here that ram-pressure deeply alters the ‘expected’¹ morphology of interacting galaxies, as clearly shown in Fig. 4. This point is extremely important to properly identify the different physical mechanisms acting on galaxies when interpreting observational results.

Since stripped tails are diffuse sources that require high-sensitivity observations with a sufficiently large field of view, only for very few of them we have detailed information coming from multiwavelength data. Our simulations indicate that we should be able to detect in X-rays heated gas ($T > 10^7 \text{ K}$) in the wake of interacting systems. At least three extended X-ray tails of late-type galaxies have been observed in clusters (UGC 6697 in A1367: Sun & Vikhlinin 2005 – ESO 137-001 in A3627: Sun et al. 2006 – C153 in A2125: Wang et al. 2004). The gas temperature measured in two of these sources is in the expected range ($T \sim 0.5 - 1.2 \times 10^7 \text{ K}$, Wang et al. 2004; Sun & Vikhlinin 2005). In ESO 137-001, the X-ray tail coincides positionally with a detected H α tail and 29 H II regions have been detected in the wake of gas (Sun et al. 2007). Similarly to the results of our simulations, the H II regions closest to the galactic disc form a bow-like front with the axis nearly in the same direction as the tail. Additionally, Sun et al. (2006) detected three possible ultra-luminous X-ray sources (ULXs) related to active star formation in the tail. In UGC 6697, hints of correlation between X-ray and H α emission have also been shown (even if on smaller scales). Additionally, at least two X-ray point sources have been detected in the tail of this galaxy, which may be associated with star clusters. The detailed analysis of Sun & Vikhlinin (2005) also demonstrates that ram pressure alone cannot explain the peculiarities of UGC 6697 (i.e. its complex velocity field, the presence of a warp in the South-East region of the stellar disc). In agreement with our numerical results, they thus suggest that, together with ram-pressure stripping, tidal effects related to galaxy interactions could play a role in determining the observed properties of UGC 6697 and its X-ray tail.

On the other hand, it has also been proven that tidal effects alone cannot explain the observational properties of some interacting galaxies. Two irregular objects (CGCG 97-073 and 97-079) located in the north-west region of the galaxy cluster A1367 show extended ($\sim 75 \text{ kpc}$) tails of H α and synchrotron emission

¹Based on the results of previous models of galaxy interactions, which do not take into account the ambient medium effects (e.g. Kapferer et al. 2005).

(Gavazzi et al. 1995, 2001b). Observations indicate that the tails host ~ 40 per cent of the original gas of the two galaxies. Gavazzi et al. (2001b) concluded that both the high star-formation rate of these irregular galaxies and their head-tail morphology can be explained by ram-pressure effects. However, due to the low-ICM density in the peripheral cluster region where the two galaxies are located, they claimed the need of an additional physical mechanism (i.e. the interaction between the two objects), able to lose their potential well, thus making ram pressure more effective in stripping and/or compressing the ISM.

The fraction of stripped gas in the wake of a given galaxy is significantly higher (and comparable to the observed value) in the case of interacting systems than in isolated ones (see Kronberger et al. 2008). The combination of a galaxy encounter and of moderate ram pressure was already suggested to be responsible for the perturbed atomic gas distribution observed in interacting galaxies (NGC 4654/NGC 4639 and NGC 4254 in the Virgo cluster, Vollmer 2003; Vollmer et al. 2005). Haynes et al. (2007) and Duc & Bournaud (2008) have recently suggested that more extended (≥ 100 kpc) H I tails can be created by galaxy harassment and high-speed galaxy collisions. Our simulations show that wakes of gas and newly formed stars of several 100 kpc are originated in interacting galaxies subject to ram pressure stripping. In addition, our results can explain: (a) the origin of the blue colour and of the ionized gas detected in several gas wakes of interacting/disturbed galaxies (e.g. Gavazzi et al. 2001a; Yoshida et al. 2002; Sun & Vikhlinin 2005; Sun et al. 2007), and (b) the existence of ULXs and isolated intracluster H II regions, observed at several tens of kpc from the closest galaxy and related to stars that have formed within the intracluster volume (e.g. Gerhard et al. 2002; Sun et al. 2007).

Finally, our results can explain the origin of the region with the highest density of star-formation activity ever observed in a local cluster (A1367, Cortese et al. 2006). Two giant galaxies and several dwarfs/extragalactic H II regions, together with an extended (≥ 150 kpc) wake of ionized gas, were observed in a compact group infalling towards the cluster centre. Both ram-pressure stripping and galaxy–galaxy interactions are extremely efficient in this case. Due to their lower velocity dispersion compared to clusters, galaxy groups are actually the natural site for tidal interactions. This group is furthermore not isolated, but moving with a high velocity (~ 1700 km s $^{-1}$) in the ICM of A1367 (Cortese et al. 2004). Note that the simulation presented in this work is not representative for high-velocity encounters/mergers in the central regions of galaxy clusters. Here, additional effects, like galaxy harassment, play an important role. On the other hand, the ram pressure increases with the ICM density and the square of the relative velocity of the galaxy with respect to the ICM. Therefore, the effect of ram-pressure stripping increases in the denser regions of galaxy clusters. The relative strength and the interplay of ram pressure in high-velocity encounters will be investigated in an upcoming paper.

5 DISCUSSION AND CONCLUSIONS

In order to investigate the influence of the ram pressure on interacting galaxies, we compared the results of a simulation of an interaction with and without a constant wind. We focus on the evolution of the star-formation rate of the interacting system and on the distribution of the different baryonic components (i.e. gas and stars). The results can be summarized as follows.

(i) The star-formation rate of the interaction is enhanced in the presence of an ambient hot (3 keV) and rare medium (10^{-28} g cm $^{-3}$)

together with ram pressure by a factor of 3 in comparison to the same interaction without the ambient medium.

(ii) The morphology of the interacting system is strongly distorted. The tidal tails and the bridge between the interacting system are completely destroyed by the ram pressure. The resulting gas and stellar mass distributions of the two galaxies would not be characterized by observers as interacting system after the first close encounter.

(iii) The amount of gas in the wake of the interacting system is 50 per cent of the total gas mass of the interacting system after 500 Myr of ram pressure acting on it. Approximately 10–15 per cent of the gas is heated up to temperatures above 1×10^7 K, which would be observable in X-rays.

(iv) After 500 Myr of ram pressure, ~ 10 per cent of all newly formed stars are formed in the wake of the interacting system at distances larger than 20 kpc behind the stellar disc in the case of the face-on ram pressure. The same behaviour can be observed in the case of the edge-on ram pressure.

(v) As the tidal tails and the gaseous bridge between the interacting system feel the ram pressure, knots of cold gas ($T < 10^5$ K) start to form and these irregular structures start to form new stars. These knots are found to contain several $10^6 M_{\odot}$ of cold gas and newly formed stars. They can be classified as ‘stripped baryonic dwarf’ galaxies. The lifetime of these ‘stripped baryonic dwarfs’ is limited by turbulence and heat conduction. If the objects are in the slipstream of the disc galaxies, they can survive for a several hundred Myr up to a Gyr. As the ram pressure in the gaseous wake is decreasing due to the decreasing relative velocities, the time-scales for Kelvin–Helmholtz instabilities are increasing as well, therefore extending the lifetime of these objects. Thermal conduction is affecting ‘stripped baryonic dwarfs’ as well, but the low densities of the surrounding ICM seems to result in evaporation time-scales at least larger than 500 Myr.

Concluding we found that interacting galaxies affected by a moderate ram pressure show a completely different behaviour compared to the case of no ram pressure acting on them. The simulations presented in this work are idealized in order to be able to distinguish between different effects. As galaxies move through a real cluster, the ram pressure changes and complex interactions with the cluster potential and other galaxies are present. These factors will be investigated in upcoming papers.

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