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, 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 three 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 \(\sim 50\%\) of the total gas of the colliding galaxies after 500 Myr the galaxies start to feel the ram pressure. Nearly \(\sim 10 - 15\%\) 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 system feel the ram pressure, knots of cold gas \((T < 1 \times 10^5 \text{K})\) start to form. These irregular structures contain several \(10^6 \text{M}_\odot\) 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, e.g. Kelvin-Helmholtz instabilities, which are not resolvable within the presented SPH 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: galaxies: interactions - intergalactic medium - galaxies: stellar content - galaxies: structure - methods: numerical - hydrodynamics

1 INTRODUCTION

Multiwavelength observations have shown that the star formation rate in interacting galaxies is enhanced in comparison to isolated galaxies (Bushouse 1987, Sulentic 1976, Stocke 1978, Solomon & Sage, 1988, Combes et al. 1994, Kewley et al. 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, Noguchi 1991, Olson & Kwan 1990 a,b, Mihos 1992, Mihos & Hernquist 1996) indicated that galaxy 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 et al. 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 et al. (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 et al. (2004). The accretion onto supermassive black holes in merging galaxies and the resulting suppression of star formation and the morphology of the elliptical remnants were investigated by Springel et al. (2005).

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 intra-cluster medium (ICM) onto the inter-stellar medium (ISM) (Gunn & Gott 1972, Cayatte et al. 1990, Kenney et al. 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 et al. 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. (2007).

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, Domairko 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. 2006). In combination with the mass losses by ram-pressure stripping was introduced, the resolution of such simulations an analytical approach.

Domainko et al. (2006). In combination with the mass losses.

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 Völker Springel. Details and analysis can be found in Springel et al. (2004). The total mass and the virial radius of the galaxies’ halo are given by

\[ M_{200} = \frac{v_{200}^2}{10 G H(z)} \quad \text{and} \quad r_{200} = \frac{r_{200}}{10 H(z)} \]  

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. The gas fraction in the disc is initially 25% 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 timescale \( t_\ast \) and the release of a certain mass fraction \( \beta \) due to supernovae (SNe). The relation can be expressed as

\[ \frac{d \rho_c}{dt} = \frac{\rho_c}{t_\ast} - \beta \frac{\rho_c}{t_\ast} = (1 - \beta) \frac{\rho_c}{t_\ast}, \]  

where \( \rho_c \) and \( \rho_\ast \) are the stellar and cold gas phase densities, respectively. The factor \( \beta \) gives the mass fraction of stars above 8M_\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 to 40 M_\odot. Each SN explosion heats the surrounding gas in the bubble leading to an evaporation of cold gas. The minimum temperature the gas can reach due to radiative cooling is 10^8K. 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 et al. 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 two. 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 a 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 two Gyrs without any interaction. The
relative velocity of the encounter is $\sim 300$ km/s, 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 through a hot ($3.6 \times 10^7$ K) and thin ($10^{-28}$ 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 one 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 homogenous density and a constant temperature.

To study the influence of ram pressure by an ambient medium acting on it.

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 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% gas content. We assigned $7 \times 10^5$ 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 $1 \times 10^6$ gas particles in a box with $3 \times 10^5$ space particles to each model galaxy. In Table 1 the number of mass resolution total mass.

| Number of particles | Mass resolution [M$_\odot$/particle] | Total mass [M$_\odot$] |
|---------------------|-------------------------------------|------------------------|
| DM halo             | $3 \times 10^5$                     | $3.5 \times 10^6$      |
| gaseous disc        | $2 \times 10^5$                     | $3.4 \times 10^4$      |
| stellar disc        | $2 \times 10^5$                     | $1 \times 10^5$        |
| ICM                 | $1 \times 10^6$                     | $1.46 \times 10^6$     |
| ICM hr$^1$          | $1 \times 10^7$                     | $1.46 \times 10^7$     |

1 high resolution

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 resolution 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.

### 2.4 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 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% gas content. We assigned $7 \times 10^5$ 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 $1 \times 10^6$ gas particles in a box with 1 high resolution.

### 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 smoothed-particle hydrodynamics (SPH) by Agertz et al. (2007). They conclude in their comparison that grid codes are able to resolve and treat dynamical instabilities and mixing, while SPH codes are not. According to
In McCarthy et al. (2007) 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 timescale (Eq. (4) McCarthy et al. 2007), based on the work of Mori & Burkert (2000) (eq.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 timescales in the range of Gyrs 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 hundred Myrs, assuming a relative velocity of 1000 km/s and the low density of the ICM. Therefore the gas clumps can be stripped completely. Many of these clumps form 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 deaccelerated to several hundred km/s relative velocities. This leads to longer Kelvin-Helmholtz timescales. 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 timescale due to thermal conductivity of a gas clump with an \( n_B \) column density of 50/cm\(^3\) and a size of 1 kpc (assuming spherical geometry) in an ambient 3.6 \( \times \) 10\(^{K} \) gas with an electron number density of 10\(^{-1} \) is in the range of 500 Myrs, 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 multi-phase multi-scale 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. 3 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, 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 (\( \sim 10^9 \) M\(_{\odot} \)) gas clumps, which cool due to radiation and form new stars. In Fig. 4 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. 5 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% of the gas in the interacting system is located 20 kpc behind the stellar discs of the system. In this gaseous wake approximately 10% of all new stars are formed after 500 Myr.

The evolution of the wake is presented in Fig. 6. 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 onto the discs leading to episodes of star formation in the disc.
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.
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.

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.

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 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% 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.

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 one Gyr of evolution in the high resolution ICM simulation (a) and normal reso-
Ram-pressure stripping of interacting galaxies

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 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 a hundred 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 the stars in the wake is a distance larger than 20 kpc to the interacting discs. Almost 20% of all newly formed stars are located at a distance of more than 20 kpc to the interacting discs. 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 onto 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 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 ($T \lesssim 10^2$ K) and newly formed stars are shown. The total gas mass, originating from the interacting system in insert (a) is $3.5 \times 10^8 \, M_\odot$, the total stellar mass present in the volume shown by insert (a) is $3.5 \times 10^7 \, M_\odot$. The total gas mass, stripped from the interacting system and presented in insert (b) is $2.3 \times 10^8 \, M_\odot$ and the total stellar mass present in insert (b) is $5.9 \times 10^7 \, M_\odot$.

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 HI 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 ten elliptical cluster galaxies or group galaxies (Kim et al. 2007, Jaltema et al. 2008 and Schindler & Diaferio 2008). Sun et al. (2006, 2007 – NGC 4525, NGC 4388 and NGC 4532/DDO 137 in Virgo: Yoshida et al. 2002, Oosterloo & van Gorkom 2005, Haynes et al. 2007, Koopmann 2007 – NGC 4531 in A1367: Gavazzi et al. 2001a,b, Sun & Vikhlinin 2005 – C153 in A2125: Wang et al. 2004 – ESO 137-001 in A3627: Sun et al. 2006 – C153 in A2125: Wang et al. 2004 – 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 ($T \sim 0.5 \sim 1.2 \times 10^7$ K, Wang et al. 2004, Sun & Vikhlinin 2005). In ESO 137-001 the X-ray tail coincides positionally with a detected Hα tail and 29 HII regions have been detected in the wake of gas (Sun et al. 2007). Similarly to the results of our simulations, the HII 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 Hα 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 disk). 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 (CCCG 97-073 and 97-079) located in the North-West region of the galaxy cluster A1367 show extended (∼75 kpc) tails of Hα and synchrotron emission (Gavazzi et al. 1995, 2001b). Observations indicate that the tails host ∼40% of the original gas of the two galaxies. Gavazzi et al. (2001b) concluded that both the high SFR 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 4524 in the Virgo cluster, Vollmer 2003, Vollmer et al. 2005). Haynes et al. (2007) and Duc et al. (2007) have recently suggested that more extended (≥100 kpc) HI 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 hundred of 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 intra-cluster HII regions, observed at several tens of kpc from the closest galaxy and related to stars that have formed within the intracluster vol-

\[^1\] Based 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).
Figure 12. The gas and stellar distribution of matter in the wake of two interacting galaxies moving face on through an ambient thin ($10^{-28}$ g/cm$^3$), hot ($5 \times 10^7$ K) medium with 1000 km/s. 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$_\odot$. 

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 HII regions, together with an extended ($\geq 150$ 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) 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 summarised as follows:

- The star formation rate of the interaction is enhanced in the presence of an ambient hot (3keV) and rare medium (10^{-24} g/cm^3) together with ram pressure by a factor of three in comparison to the same interaction without the ambient medium.
- 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 characterised by observers as interacting system after the first close encounter.
- The amount of gas in the wake of the interacting system is 50% of the total gas mass of the interacting system after 500 Myr of ram pressure acting on it. Approximately 10-15% of the gas is heated up to temperatures above 1 \times 10^7 K, which would be observable in X-rays.
- After 500 Myr of ram pressure ∼ 10% 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.
- 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_⊙ 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 Myrs up to a Gyr. As the ram pressure in the gaseous wake is decreasing due to the decreasing relative velocities, the timescales for Kelvin-Helmholtz instabilities is 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 timescales at least larger than 500 Myrs.

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 idealised 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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