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Ram pressure stripping of spiral galaxies in clusters

Mario G. Abadi,[1,2] Ben Moore[1] and Richard G. Bower[1]
[1]*Department of Physics, University of Durham, South Road, Durham DH1 3LE*
[2]*Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, 5000 Córdoba, Argentina*

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ABSTRACT

We use three-dimensional SPH/*N*-body simulations to study ram pressure stripping of gas from spiral galaxies orbiting in clusters. We find that the analytic expectation of Gunn & Gott, relating the gravitational restoring force provided by the disc to the ram pressure force, provides a good approximation to the radius at which gas will be stripped from a galaxy. However, at small radii it is also important to consider the potential provided by the bulge component. A spiral galaxy passing through the core of a rich cluster, such as Coma, will have its gaseous disc truncated to $\sim 4\,\mathrm{kpc}$, thus losing ~ 80 per cent of its diffuse gas mass. The time-scale for this to occur is a fraction of a crossing time $\sim 10^7$ yr. Galaxies orbiting within poorer clusters, or inclined to the direction of motion through the intracluster medium, will lose significantly less gas. We conclude that ram pressure alone is insufficient to account for the rapid and widespread truncation of star formation observed in cluster galaxies, or the morphological transformation of Sabs to S0s that is necessary to explain the Butcher–Oemler effect.

Key words: galaxies: clusters: general – galaxies: kinematics and dynamics.

1 INTRODUCTION

There is a long-standing debate concerning the effect of environment on galaxy morphology. The pioneering work of Butcher & Oemler (1978, 1984) first demonstrated that distant clusters contained a far higher fraction of blue galaxies than their local counterparts. Subsequent work has established that many of the red galaxies in these clusters have spectral signatures of recent star formation (Dressler & Gunn 1983; Couch & Sharples 1987; Poggianti et al. 1998; van Dokkum et al. 1998). The most recent advances have been made with the *Hubble Space Telescope*, which allows the morphology of the distant galaxies to be directly compared with the properties of their nearby counterparts. The studies of Dressler et al. (1997) and Couch et al. (1998) suggest that the predominant evolutionary effects are that the distant clusters have a substantial deficit of S0 systems compared with nearby systems, and at lower luminosities they contain primarily Sc–Sd spirals, compared with the large population of dwarf spheroidals in present-day clusters.

Many authors have suggested that the predominance of early-type S0 galaxies in local clusters is the result of a mechanism that suppresses star formation in these environments, leading to a transformation of galaxy morphology. Comparison of the galaxy population of local and distant clusters provides the strongest evidence for this. This leads to the natural conclusion that the primary effect of the cluster environment is to transform luminous spiral galaxies into S0 types through suppression of their star formation.

A key ingredient in the explanation of the Butcher–Oemler effect is the rate at which ‘fresh’ galaxies are supplied from the field into the cluster environment. The differences in the fractions of blue, or actively star-forming, galaxies between local and distant clusters may result either from an increase in the general level of star formation activity at higher redshift (e.g. Lilly et al. 1996; Cowie et al. 1997), or from a different level of infall between local and distant clusters (Bower 1991; Kauffmann 1996).

Several mechanisms have been proposed that may be capable of explaining the transformation of galaxy morphology in dense environments. Ram-pressure stripping has been a long-standing possibility, dating from the analytic work of Gunn & Gott (1972), and a mechanism that has been cited in over 200 published abstracts. As a galaxy orbits through the cluster, it experiences a wind because of its motion relative to the diffuse gaseous intracluster medium (ICM). Although the ICM is tenuous, the rapid motion of the galaxy causes a large pressure front to build up in front of the galaxy. Depending on the binding energy of the galaxy's own interstellar medium, the ICM will either be forced to flow around the galaxy or will blow through the galaxy, removing some or all of the diffuse interstellar medium. Related mechanisms to ram pressure are thermal evaporation of the interstellar medium (Cowie & Songaila 1977) and viscous stripping of galaxy discs (Nulsen 1982). These occur even when the ram pressure is insufficient to strip the gas disc directly: turbulence in the gas flowing around the galaxy entrains the interstellar medium resulting in its depletion.

If ram pressure or viscous stripping is effective at removing gas, then cluster spirals should have truncated discs deficient in H I.

Observational evidence for this is marginal. Some galaxies show clear evidence for stripping, e.g. NGC 4522 (Kenney & Koopmann 1999), UGC 6697 (Nulsen 1982) or several Virgo cluster galaxies (Cayatte et al. 1994). However, a larger survey of 67 cluster galaxies showed no evidence of these effects (Mould et al. 1995).

Interactions between galaxies are another possible agent for promoting morphological transformation. However, strong interactions that lead to galaxy merging are unlikely to be an effective mechanism in virialized clusters of galaxies, because the relative velocity of galaxies is too high for such encounters to be frequent (Ghigna et al. 1998). Moore et al. (1996) examined the effects of rapid gravitational encounters between galaxies or with the lumpy potential structure of clusters. This mechanism has been termed galaxy 'harassment' and is highly effective at transforming fainter Sc–Sd galaxies to dSphs and even tidally shredding LSB galaxies. Although this mechanism can account for the observed evolution of lower luminosity galaxies in clusters, the concentrated potentials of luminous Sa–Sb galaxies help to maintain their stability (Moore et al. 1999), although their discs are substantially thickened.

A final mechanism that should not be overlooked is the truncation of star formation through the removal of the hot gas reservoir that is thought to surround galaxies (Larson, Tinsley & Caldwell 1980; Benson et al., 1999). In clusters, any hot diffuse material originally trapped in the potential of the galaxies halo becomes part of the overall ICM. The galaxy (with the possible exception of the central dominant galaxy) cannot supplement its existing ICM and thus is doomed to slowly exhaust the material available for star formation. This mechanism is the only environmental mechanism currently embedded into hierarchical galaxy formation codes (e.g. Kauffmann & Charlot 1998; Baugh et al. 1998); however, it appears unable to reproduce adequately the star formation histories of real cluster galaxies, because the spectroscopic studies require that star formation is suppressed on far shorter time-scales (e.g. Barger et al. 1996; Poggianti et al. 1998).

In this paper, we revisit ram pressure stripping as a mechanism for the removal of gas from cluster galaxies and thus rapid suppression of the star formation rate. In particular, we use fully three-dimensional SPH simulations to compare our results with the analytic estimate of Gunn & Gott, and to investigate the effect of differing galaxy infall velocities, inclinations and cluster gas densities. Our main motivation is to investigate whether ram pressure could be effective in clusters less rich than the Coma cluster, and to determine whether the stripping effect is limited only to the outer part of the disc or whether the effects can propagate inwards. It is also of interest to determine the time-scale on which the stripping should occur, because rapid truncation of star formation appears to be one of the key signatures of the spectroscopic Butcher–Oemler effect.

Relatively little numerical work has been performed to examine the effects of ram pressure, especially three-dimensional simulations (c.f. Farouki & Shapiro 1980). Balsara, Livio & O'Dea (1994) performed several high-resolution simulations of the gas stripping process using an Eulerian code, but again using a restricted two-dimensional version. As well as being able to study the rich structure of the gas ablation process, these authors found that the galaxy could accrete gas from the downstream side of the flow. We note that Kundic, Spergel & Hernquist (1993) also reported a preliminary investigation of this problem using a smoothed particle hydrodynamic (SPH) code.

The structure of this paper is as follows. In Section 2 we discuss the parameters of the galaxy model that we shall use and make predictions for the radius at which gas will be stripped via ram pressure. Techniques and results of numerical SPH simulations are presented in Section 3, and are discussed in Section 4, along with the shortcomings of ram pressure stripping as the mechanism behind the Butcher–Oemler effect.

2 THE GALAXY MODEL

We construct an equilibrium galaxy model designed to represent the Milky Way, using the techniques described by Hernquist (1993). The model has a stellar and a gaseous disc, halo and bulge components. The bulge is spherical and has a mass density profile of the form

$$\rho_\mathrm{b}(r) = \frac{M_\mathrm{b}}{2\pi r_\mathrm{b}^2}\frac{1}{r(1+r/r_\mathrm{b})^3}, \tag{1}$$

where r_b is the scalelength and M_b is the mass. The model has a dark matter halo with density given by the following truncated profile:

$$\rho_\mathrm{h}(r) = \frac{M_\mathrm{h}}{2\pi^{3/2}}\frac{\alpha}{r_\mathrm{t} r_\mathrm{h}^2}\frac{\exp(-r^2/r_\mathrm{t}^2)}{(1+r^2/r_\mathrm{h}^2)}, \tag{2}$$

where r_h is the core radius, r_t is the truncation radius and M_h is the mass. The mass normalization requires that the constant should be

$$\alpha = 1/\{1 - \pi^{1/2} q \exp(q^2)[1 - \mathrm{erf}(q)]\}, \tag{3}$$

where $\mathrm{erf}(q)$ is the error function and $q = r_\mathrm{h}/r_\mathrm{t}$. The disc is axisymmetric and is composed of both stars and gas. Its mass density profile is an exponential of the form

$$\rho_\mathrm{d}(R,z) = \frac{M_\mathrm{d}}{4\pi R_\mathrm{d}^2 z_\mathrm{d}}\exp(-R/R_\mathrm{d})\,\mathrm{sech}^2(z/z_\mathrm{d}), \tag{4}$$

where R_d, z_d and M_d are the cylindrical scalelength, the vertical thickness and mass, respectively. We will replace the subscript 'd' by 's' to refer to the stellar disc, or 'g' to refer to the gaseous disc.

The characteristic length-scales of each component are listed in Table 1 and we plot the contribution to the rotational velocity of the disc provided by each component in Fig. 1. Dark matter begins to dominate the baryonic components beyond ~ 10 kpc, and the maximum rotational velocity of the disc is 220 km s^{-1}. Adopting a *B*-band mass to light ratio of 2, the central surface brightness of the model galaxy is ~ 21 mag arcsec^{-2}.

Table 1. The main parameters of each component of the model spiral galaxy.

	N	M_total	m_p	$[L]$ (kpc)	ϵ (kpc)
ICM	16 000	0.24	1.47e-5		0.75
Disk(gas)	8000	1.12	1.40e-4	3.5 0.35	0.28
Disk(stars)	8000	4.48	5.60e-4	3.5 0.35	0.28
Bulge	2500	1.68	6.72e-4	0.5	0.21
Halo	8000	21.28	2.66e-3	3.5 24.5	1.40
Total	42 500	28.58			

Notes.
N is the number of particles; M_total is total mass of each component (for the ICM, this is quoted assuming the value for a density equal to the core of the Coma cluster); m_p is the mass per particle for each component, all expressed in units of $10^{10}\,\mathrm{M}_\odot$. $[L]$ is the characteristic length-scale of the different components (for the disc we quote R_d and z_d; for the halo we quote τ_h and r_t). ϵ is the gravitational softening.

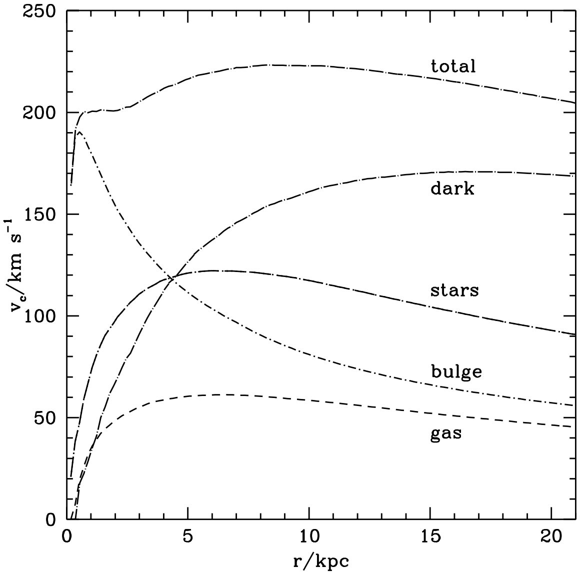

Figure 1. The contribution from each component of the model galaxy to the rotational velocity of the disc.

3 ANALYTIC SOLUTION

We have applied the ideas of Gunn & Gott (1972) to the galaxy model in order to obtain analytic estimates of the radius beyond which the gas will be stripped, $R_{\rm str}$, when the galaxy is moving through the intracluster medium (ICM). These authors stated that the gaseous disc will be removed if the ram pressure of the ICM is greater than the restoring gravitational force per unit area provided by the disc of the galaxy(c.f. Sarazin 1986). In this case, the ram pressure is $P = \rho_{\rm icm} v^2$, where v is the velocity of the galaxy with respect to the ICM and $\rho_{\rm icm}$ is the gas density of the ICM. The restoring gravitational acceleration of a particle orbiting in the galaxy is $\partial\phi/\partial z$, where z is the coordinate perpendicular to v. The total gravitational potential, ϕ, of the galaxy can be obtained by solving the Poisson equation $\nabla^2\phi(R,z) = 4\pi G\rho(R,z)$ for each component separately and summing. In the case of a face-on passage, we have for the bulge

$$\frac{\partial\phi_{\rm b}}{\partial z}(R,z) = \frac{GM_{\rm b}}{(r+r_{\rm b})^2}\frac{z}{r}, \tag{5}$$

and for the halo

$$\frac{\partial\phi_{\rm h}}{\partial z}(R,z) = \frac{2\alpha GM_{\rm h}}{\pi^{1/2}r^2}\frac{z}{r}\int_0^{r/r_{\rm h}}\frac{x^2\exp(-x^2)}{x^2+q^2}\,{\rm d}x. \tag{6}$$

The analytical solution of the Poisson equation for the disc is not so straightforward as for the spherical components. Binney & Tremaine (1987) use separation of variables to solve this problem for the case of an infinitely thin disc with a surface density

$$\sigma_{\rm d}(R) = \int_{-\infty}^{\infty}\rho_{\rm d}(R,z)\,{\rm d}z = \frac{M_{\rm d}}{2\pi R_{\rm d}^2}\exp(-R/R_{\rm d}). \tag{7}$$

We have adopted this approximation and used their formula (2-167) in order to compute the restoring gravitational acceleration for the disc:

$$\frac{\partial\phi_{\rm d}}{\partial z}(R,z) = GM_{\rm d}\int_0^{\infty}\frac{J_0(kR)\exp(-k|z|)}{[1+(kR_{\rm d})^2]^{3/2}}k\,{\rm d}k, \tag{8}$$

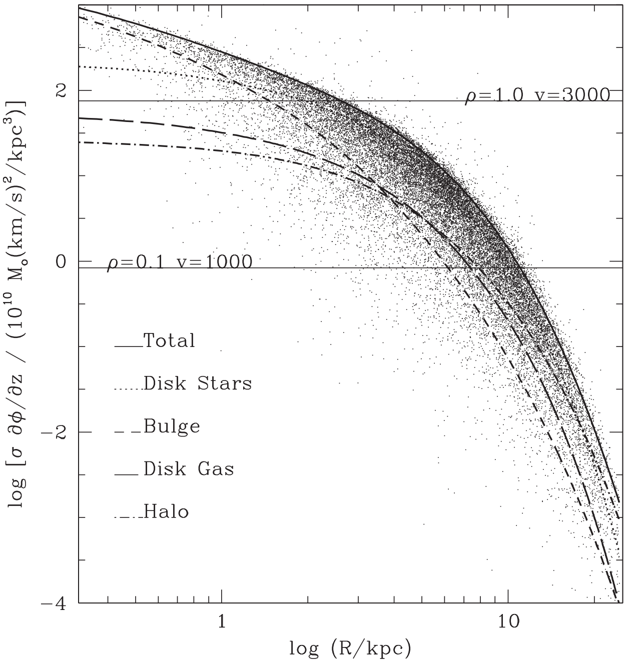

Figure 2. The component of the force in the direction z perpendicular to the velocity flow, as a function of cylindrical radius for each component. The curves show the total contribution for each component of the model galaxy whilst the dots show values calculated at the positions of each individual particle. The horizontal lines show the ram pressure force for representative velocities and ICM densities.

where $J_0(x) = \pi^{-1}\int_0^{\pi}\cos(x\sin\theta)\,{\rm d}\theta$ is the Bessel function of the first kind of order zero. The stripping radius, $R_{\rm str}$, can then be computed by solving the equation

$$\frac{\partial\phi}{\partial z}(R,z)\sigma_{\rm g}(R) = \rho_{\rm icm}v^2, \tag{9}$$

where the left-hand side is the total restoring gravitational force per unit mass of the model and the right-hand side is the ram pressure. At a given radius, R, the restoring gravitational force per unit mass is a function of the coordinate z. This force is maximum at $z = 0$, therefore in order to completely remove the gas from the galaxy the ram pressure must be greater than this value.

In Fig. 2 we plot both sides of equation (9) (solid lines), for the parameters quoted in Table 1, which were chosen to represent observational values for an Sb type spiral galaxy like the Milky Way. We also show the contribution of each component to the maximum restoring force per unit mass as a function of the radius. The dots show the value of the total gravitational force per unit area computed directly from all particles of the N-body realization. The agreement between the analytical estimates (solid curved line) and the envelope of values computed from the particles (dots) demonstrates the validity of using equation (8).

The ram pressure values for two different ICM densities and relative velocities are shown as horizontal lines in Fig. 2. These may be representative of galaxies passing through the core of the Coma and Virgo clusters. The predicted radius of the final stripped gas disc, $R_{\rm str}$, is given by the intersection of the horizontal line with the total restoring force per unit area (solid curved line), roughly 3 kpc and 10 kpc for the values illustrated here. For $R < R_{\rm stp}$ the restoring gravitational force per unit mass is greater than the ram pressure and the gas remains bound to the galaxy. In contrast, for $R > R_{\mathrm{str}}$ the ram pressure overcomes the gravitational force and the gas can be stripped.

Fig. 2 demonstrates that the main contribution to the total restoring gravitational force comes from the stellar disc, although in the central parts of the galaxy the bulge becomes important. For this model, the bulge contributes 30 per cent of the disc mass and dominates the vertical potential in the central 2 kpc. The halo provides a negligible contribution within 10 kpc, but begins to dominate on scales $\gtrsim 20$ kpc.

One interesting and straightforward application of this model is the comparison of R_{str} with the H I observational data available for galaxies in clusters. Cayatte et al. (1994) analyse the surface brightness of 17 bright spirals in the Virgo cluster. They divided the sample into four subsamples according to the shape of the surface brightness profile and conclude that ram pressure is the main reason for gas removal in subsample III (three galaxies). They also present a list of isophotal H I and optical diameters for these galaxies.

We solved equation (9) for a ram pressure corresponding to $\rho_{\mathrm{icm}} = 0.1\rho_{\mathrm{C}}$ and $v = 1000\,\mathrm{km\,s^{-1}}$, with different values of the scalelength of the galaxy R_{d}. In order to compare our results directly with the observations we define an 'optical' radius R_{o} as the size of the stellar disc. Then, we scale linearly from R_{d} to R_{o}. For $R_{\mathrm{d}} = 3.5$ kpc, this value is $R_{\mathrm{o}} = 24$ kpc and at this position the density has decreased by a factor $\sim 10^{-3}$. In Fig. 3 we show the ratio of the stripping radius to 'optical' radius, $R_{\mathrm{str}}/R_{\mathrm{o}}$, as a function of R_{o} for the model (solid line). The filled circles show the observed radii obtained by Cayatte et al. (1994) for their galaxies and we find reasonable agreement between the model and the data.

4 NUMERICAL SIMULATIONS

Hydrodynamical simulations of the ram pressure require enough spatial resolution to follow the interaction between the 'cold' disc gas and the hot ICM. If the ICM particles are too massive, then they will punch holes in the gas disc like bullets and the flux of particles against the disc will be dominated by shot noise. With current computational resources, simulations that attempt to capture the full cosmological context of the formation of discs and their subsequent evolution within a cluster environment will be completely dominated by numerical effects.

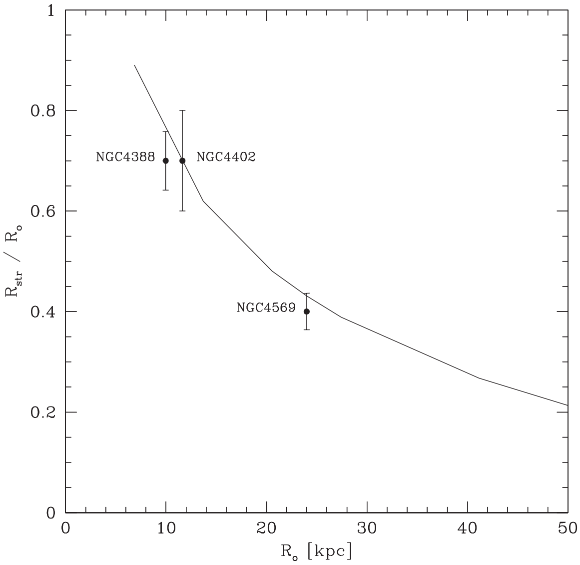

Figure 3. Dependence of the stripping radius, R_{str}, as a function of the the disc scalelength, R_{d}.

Ideally, gas particles will flow on to the disc, imparting a significant fraction of their momentum as their motion is halted by the disc gas. Too hot to accrete on to the disc, they will be forced to flow around it and rejoin the ICM. To achieve this spatial resolution, the ICM particles should have a mass that is at least as small as that of the disc gas. The limitation in the number of gas particles that SPH codes can handle makes it impossible to follow the evolution of a galaxy through an entire cluster.

For example, the mass of gas inside the Abell radius $r_{\mathrm{A}} = 1.5\,h^{-1}$ Mpc for the Coma cluster is $M_{\mathrm{icm}} = 5 \times 10^{13}\,h^{-5/2}\,\mathrm{M}_{\odot}$ (White et al. 1993). On the other hand, the H I component of a massive galaxy is $M_{\mathrm{g}} \sim 10^{10}\,\mathrm{M}_{\odot}$ (Canizares et al. 1986; Young et al. 1989) so that the ratio between the number of gas particles in the ICM and the galaxy would be $\sim 10^{4}$. With just 10^{5} SPH particles, a galaxy passing pericenter will encounter of order 10–100 gas particles. These will detonate the disc like nuclear explosions, leaving large holes and creating a large artificial drag. To suppress this effect, a minimum ICM gas mass equal to the disc particle mass is necessary, requiring $N \sim 10^{7-8}$ gas particles for the ICM.

To avoid this problem we simulate only the passage of the galaxy through the cluster core, where ρ_{icm} and v are maximum and the ram pressure stripping is most effective. We represent the ICM as a flow of particles along a cylinder of radius $R_{\mathrm{cyl}} = 30$ kpc and thickness $z_{\mathrm{cyl}} = 10$ kpc. The axis of the cylinder is oriented in the z-direction, perpendicular to the plane of the galaxy in the face-on case. We also carry out simulations in which the galaxy is passing edge-on and inclined at 45° to the direction of motion through the ICM, for which we use a box of size 60 kpc × 60 kpc × 10 kpc. Initially, we randomly distributed $N_{\mathrm{icm}} = 16\,000$ gas particles inside the cylinder ($N_{\mathrm{icm}} = 20\,000$ for the box) with a density ρ_{icm} and a temperature T. We have chosen the temperature $T = 8$ keV and the density to range from the central density of a cluster like Coma, $\rho_{\mathrm{icm}} = \rho_{\mathrm{C}} \equiv 5.64 \times 10^{-27}\,h_{50}^{1/3}\ \mathrm{g\,cm^{-3}}$ (Briel, Henry & Bohringer 1992), to the density of a cluster like Virgo, $\rho_{\mathrm{icm}} = 0.1\rho_{\mathrm{C}}$. (Throughout this paper we have adopted a value for the Hubble constant of $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.)

Table 2. Main characteristics of the simulations.

run	ρ/ρ_{C}	v ($\mathrm{km\,s^{-1}}$)	flow
A	0.0	0	isolation
B	0.1	1000	face-on
C	0.1	2000	face-on
D	0.1	3000	face-on
E	1.0	1000	face-on
F	1.0	2000	face-on
G	1.0	3000	face-on
H	1.0	2000	edge-on
I	1.0	2000	45°

Notes.
Column 1 is the name of the run, ρ/ρ_{C} is the density of the intracluster medium in units of the central density of Coma cluster, v is the velocity of the flow of the intracluster medium in $\mathrm{km\,s^{-1}}$, 'flow' is the orientation of the galaxy with respect to the velocity of the intracluster medium.

In order to represent the passage of the galaxy through the ICM, we give all gas particles in the cylinder an initial velocity v. We also carried out a test simulation in which we increased the density of ICM particles from an initial value of zero, such that the galaxy feels a gradual increase in pressure, rather than a sudden shock. The final stripping radius was the same as in the case of an instantaneous wave of particles of the full density. This allows us to save an important fraction of computational time.

We have used the TREE-SPH code developed and kindly made available by Navarro & White (1993). We have modified this code in order to include periodic boundary conditions for ICM gas particles that leave the cylinder or the box. Each particle that leaves the cylinder or the box at $z_{\rm cyl}/2$ is re-entered at $-z_{\rm cyl}/2$. We also apply reflecting boundary conditions for particles that leave the cylinder edges at $x^2 + y^2 = R^2_{\rm cyl}$. In Table 2 we list the main characteristics of the simulations. The code has individual time-steps that are typically $\sim 10^4$ yr and we run each simulation for more than 10^8 yr.

In Figs 4 and 5 we show the projected distribution of disc gas particles at the final output (x–y plane and x–z plane, respectively) for four of the simulations. Run A is the model galaxy in isolation, runs F, H and I are face-on, edge-on and inclined 45° to the direction of motion. At the final time-step, the distribution of stars and dark matter particles remain very similar to the initial conditions, whereas the gas distribution is strongly modified by the ram pressure.

In Fig. 6, we show the evolution of the radius $R_{\rm str}$, and the fraction of gas mass that remains inside this radius. We estimate $R_{\rm str}$ as the radius of the most distant gaseous disc particle from the centre, and the mass is calculated using the disc particles inside a cylinder of radius $R_{\rm str}$ and thickness of 1 kpc. The dotted and solid curves correspond to simulations B to G (face-on) from top to bottom, respectively, i.e. monotonically increasing the amount of ram pressure. The short-dashed line corresponds to simulation H (edge-on) and the long-dashed line to simulation I (inclined 45°).

In Fig. 7 we have plotted the stripping radius, $R_{\rm str}$, as a function of the velocity v of the ICM. The curves show the analytical solution of equation (9) for different values of density: $\rho_{\rm icm} = 0.1\rho_{\rm C}$ (dotted line), $\rho_{\rm icm} = \rho_{\rm C}$ (solid line) and $\rho_{\rm icm} = 10.0\rho_{\rm C}$ (dashed line). For each ICM density, the upper curve shows the solution taking into account the restoring gravitational force of all components of the galaxy, and the lower corresponds to including just the stellar disc. The filled squares are the values measured from the numerical simulations of the face on passages, whilst the open square denotes the edge-on simulation. The open triangle shows the 45° simulation, which is intermediate between face- and

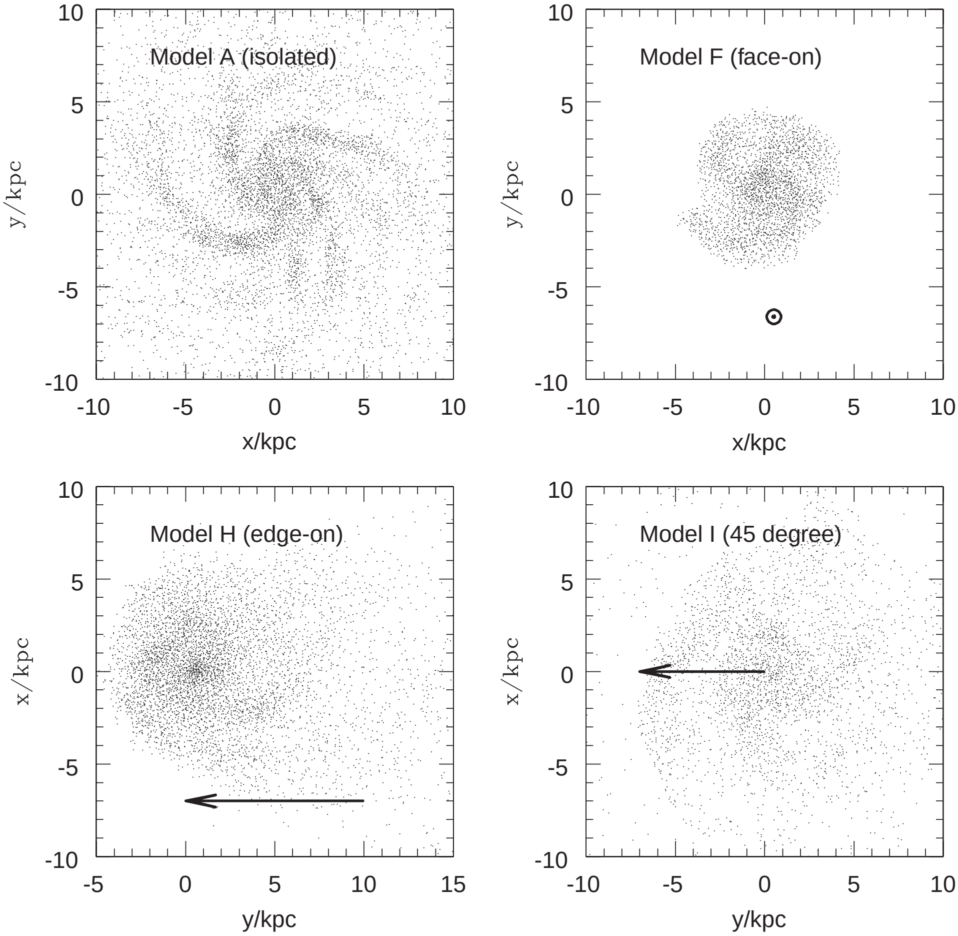

Figure 4. The positions of the gas particles plotted in the x–y plane (face-on) after $\sim 10^8$ yr of evolution. The arrows indicate the direction of motion (run A is the model in isolation).

edge-on. We also show as filled circles the observational radius from Cayatte et al. (1994) for three galaxies in the Virgo cluster, assigned a velocity of $1200\,\mathrm{km\,s^{-1}}$.

5 DISCUSSION

The motivation for this paper was to examine the effectiveness of ram pressure stripping at removing the reservoir of cold gas from spiral galaxies. In particular, could ram pressure be the key mechanism behind the Butcher–Oemler effect by rapidly truncating star formation in cluster galaxies?

In the Introduction, we outlined how a simple explanation of the Butcher–Oemler effect might work. New galaxies are supplied to the dense cluster environment from the field. The evolution of the rate of this supply is well described by numerical models for the evolution of gravitational structure, or their analytical approximations (e.g. Kauffmann 1996). Another important factor is the level of star formation activity in the galaxies before they feel the influence of the cluster. It is generally believed that star formation levels are higher in the intermediate-redshift universe than locally (Lilly et al. 1996; Cowie et al. 1997; Steidel et al. 1998).

The second ingredient of the explanation is the effect of the cluster environment on the evolution of the star formation rates of galaxies. A general decline is expected, because galaxies in the cluster will gradually consume the gas in their discs, and the possible sources of replenishment, such as high-velocity clouds or gas-rich satellites, will be stripped away. However, a slow decline is not adequate to explain the strong Balmer absorption line spectra frequently seen in the cluster galaxies (Couch & Sharples 1987; Barger et al. 1996). In order to match the strength of such lines, a sudden decrease in the star formation rate is required (Poggianti & Barbaro 1996). In the more extreme cases, the line strength can only be matched if the truncation is preceded by a burst of star formation; a burst would make the age distribution of the weaker lined systems easier to understand as well.

Galaxy harassment could provide the mechanism to initiate a burst of star formation once a galaxy enters the cluster environment. It is also very efficient at causing instabilities that drive large amounts of gas to the central regions of spirals (Lake, Katz & Moore 1998), although these processes are less efficient in luminous spirals (Moore et al. 1999). The numerical experiments of this paper put us in the position to assess the plausibility of ram pressure stripping as the truncation mechanism. Initially, this scenario seems promising. In the Coma cluster environment, the wind from the ICM causes a substantial reduction in the size of gaseous discs. Indeed, Bothun & Dressler (1986) find several

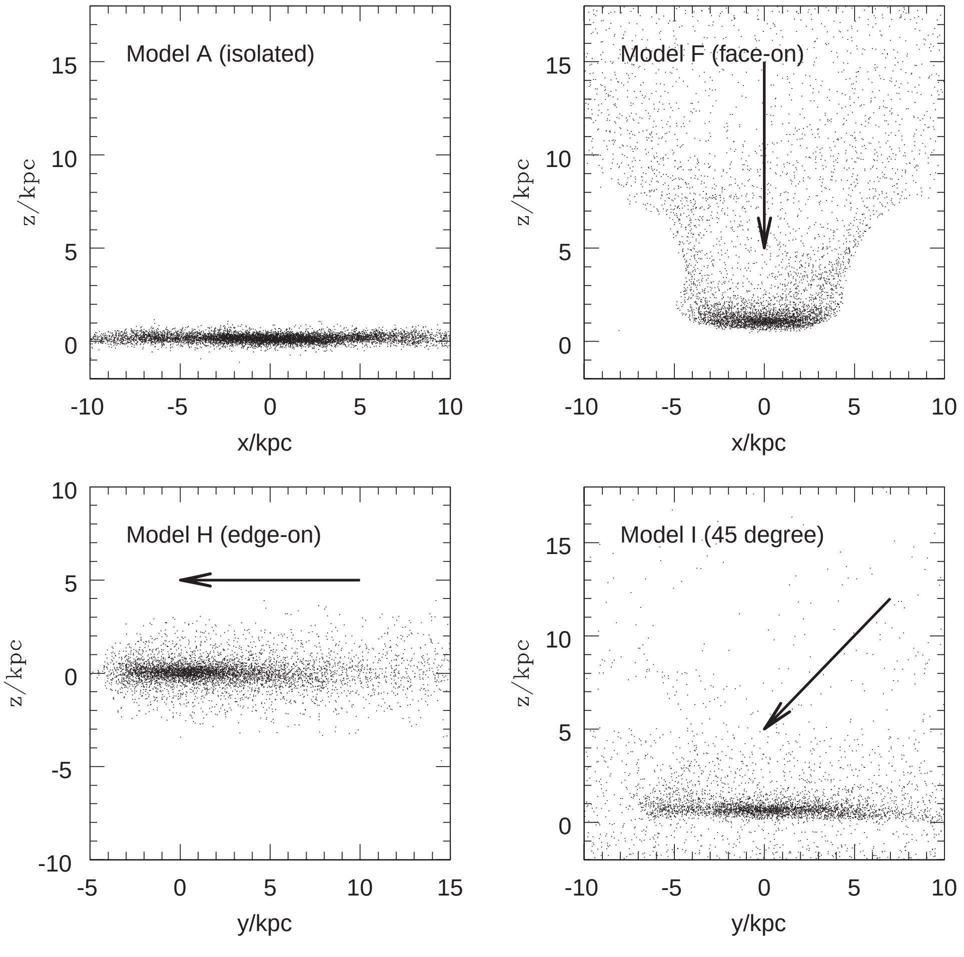

Figure 5. The positions of the gas particles plotted in the x–z plane (edge-on) after $\sim 10^8$ yr of evolution. The arrows indicate the direction of motion (run A is the model in isolation).

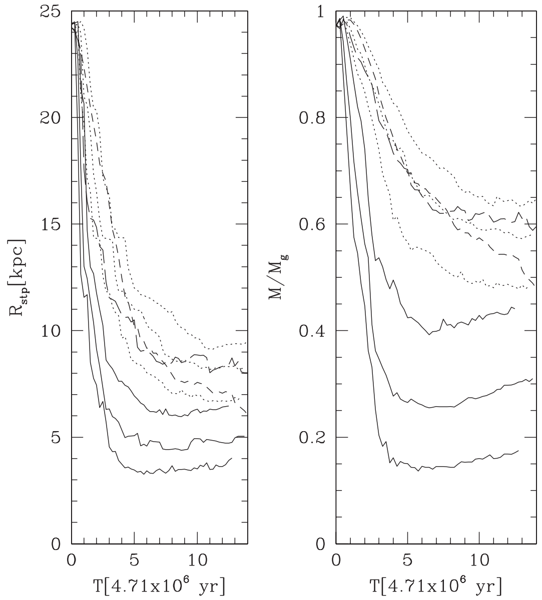

Figure 6. Evolution of the radius and mass of the gas disc as a function of time. Both rapidly converge on a time-scale $\sim 5\times10^7$ yr. From top to bottom, the dotted and solid lines show the effects of stripping for velocities of 1000, 2000 and 3000 km s^{-1} for $\rho = 0.1\rho_C$ and $\rho = 1.0\rho_C$. The short- and long-dashed lines are for the edge-on and 45° simulations with a velocity of 2000 km s^{-1} and $\rho = 1.0\rho_C$.

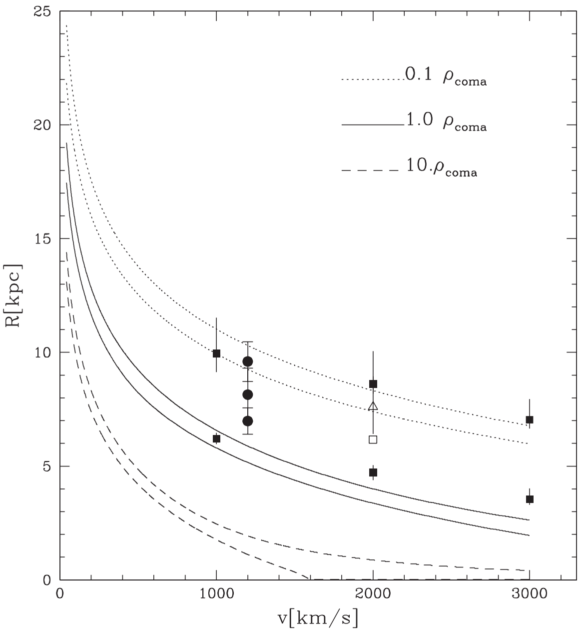

Figure 7. The size of the stripped gas disc, R_{str}, as a function of the velocity flow for different cluster gas densities. The filled squares are from our simulations of face-on encounters, the open square and triangle are for edge-on and 45° encounters.

starbursting, H I deficient spirals in the core of the Coma cluster. The time-scale for this is very rapid and is shorter than the time taken to cross the cluster core. However, beyond this superficial success, a number of problems remain to be addressed.

(i) The largest deficit of this model is that in no case is the gas disc completely removed. A substantial portion of the cold gas remains sufficiently bound to the stellar disc such that the external medium prefers to flow around the system. In the most extreme case, of a galaxy passing through the core of the Coma cluster at 3000 km s^{-1}, the disc is truncated at $\sim$ 1.5 disc scalelengths. We can estimate the corresponding reduction in the star formation rate using the Schmidt star formation law (Schmidt 1959; Kennicutt 1989) to calculate the contribution to the overall star formation rate at each radius. For the unfortunate galaxy mentioned above, the star formation rate will be reduced by a factor of 2. In lower density environments, the effect is much lower: stripping the disc beyond 3 scalelengths reduces the star formation rate by only 10 per cent. Fujita & Nagashima (1999) recently examined the colour evolution of spiral galaxies that have suffered ram pressure stripping with similar conclusions.

(ii) Several authors find that the star formation rate in cluster galaxies is significantly reduced between the field and the cluster centre (Dressler et al. 1997; Balogh et al. 1998; Poggianti et al. 1998). Even when the diffuse gaseous material is stripped from the disc, additional gas will remain in the form of dense molecular clouds. These cannot be removed by the ram pressure force because they are so small and dense. In local Sa–Sc galaxies, the mass of molecular gas can equal the atomic gas fraction (Young & Scoville 1991).

(iii) Comparison of the stripped gas fractions for galaxies in the cores of the Coma and Virgo cluster clusters shows that ram pressure is only a significant force in the densest regions. In contrast, the data of Balogh et al. (1998), and of Morris et al. (1998), suggest that the influence of the environment extends out to as much as twice the cluster virial radius. Some of this effect probably comes from galaxies that are embedded in groups and poor clusters that are part of the large-scale structure around the cluster. Secondly, galactic orbits in clusters that form in a hierarchical universe are fairly radial. Ghigna et al. (1998) demonstrated that 20 per cent of cluster galaxies orbit with apocentre to pericentre ratios larger than 10:1. Thus, 20 per cent of galaxies that have orbited through the core of the Coma cluster may be found at, or beyond, the virial radius. Nevertheless, to explain this effect fully we require a mechanism that is effective in environments less dense than the core of the Coma cluster.

(iv) Finally, we note that our simulations provide no explanation linking the stripping of gas with a burst of star formation, as is required to explain the most extreme absorption-line spectra. The lack of such a link most likely results from physical processes that have been omitted from our simulations. For instance, in the edge-on case, the effect of the wind is to compress the leading edge of the disc substantially. It is quite plausible that this compression could lead to an increase in the collision rate of molecular clouds, leading to a substantial enhancement in the star formation rate. Fujita (1998) discusses the proposed mechanisms for inducing starbursts in cluster galaxies, concluding that galaxy-harassment is the most viable candidate.

This discussion suggests that simple ram pressure stripping does not adequately explain the sharp decline of star formation seen in Butcher–Oemler galaxies. One possibility is that our models need to be generalized to include explicitly the effects of star formation and galaxy harassment. This will tend to make galaxies more susceptible to the ram pressure of the ICM: first because the molecular clouds that are disrupted by star formation will not be able to re-form if the diffuse material has already been removed from the disc, and secondly because tidal shocks via galaxy harassment may tend to make the disc structure more diffuse (and therefore more susceptible to stripping); this process could be particularly important if the effect of the stripping were to promote a burst of star formation.

We note that the restricted Eulerian treatment of this problem by Balsara et al. (1994) found that cooling gas may accrete back into the galaxy. We do not observe this phenomenon, but this is because of our resolution in low-density regions which are better resolved using grid-based techniques. We are addressing this problem using higher resolution simulations performed using parallel SPH and Eulerian codes.

6 CONCLUSIONS

We analyse the ram pressure stripping process of a spiral galaxy passing through the ICM using hydrodynamical simulations and we make the following conclusions.

(i) Ram pressure stripping is an effective mechanism at depleting gas from cluster spirals. The radius to which gas is removed can be calculated by equating the ram pressure force ρv^2 to the restoring force provided by the disc, as originally suggested by Gunn & Gott (1972).

(ii) Bulges provide an additional gravitational force that dominates the holding force in the central few kpc. Even a Milky Way type spiral crossing the core of the Coma cluster at $3000\,\mathrm{km\,s^{-1}}$ will retain gas within the central region.

(iii) The time-scale for gas to be removed is very short, $\sim 10^7$ yr, a fraction of a crossing time, whereas the time-scale for gravitational interactions (galaxy harassment) to affect morphology and induce star formation is of the order of a cluster crossing time.

(iv) Discs moving through clusters with orbital inclination edge-on to the direction of motion lose about 50 per cent less gas than a full face-on encounter with the ICM.

(v) Observations of the H I distribution in cluster spirals show evidence for tidally truncated discs by an amount roughly in accordance with analytic expectations.

(vi) Ram pressure stripping alone does not provide the physical mechanism behind the origin of the Butcher–Oemler effect.

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