Ram pressure stripping of spiral galaxies in clusters

Mario G. Abadi\textsuperscript{1,2}, Ben Moore\textsuperscript{1} & Richard G. Bower\textsuperscript{1}

\textsuperscript{1}Department of Physics, University of Durham, South Road, DH1 3LE, Durham, UK
\textsuperscript{2}Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, 5000 Córdoba, Argentina

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ABSTRACT

We use 3-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 (1972) relating the gravitational restoring force provided by the disk to the ram pressure force, provides a good approximation to the radius that 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 disk truncated to $\sim 4$ kpc, thus losing $\sim 80\%$ of its diffuse gas mass. The timescale for this to occur is a fraction of a crossing time $\sim 10^7$ years. Galaxies orbiting within poorer clusters, or inclined to the direction of motion through the intra-cluster 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 Sab's to S0's that is necessary to explain the Butcher-Oemler effect.

Key words: galaxies: ram-pressure.

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 counter-parts. 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, van Dokkum et al., 1998, Poggianti et al., 1998). The most recent advances have been made with the Hubble Space Telescope that allows the morphology of the distant galaxies to be directly compared with the properties of their nearby counter-parts. The studies of Dressler \textit{et al.} (1997) and Couch \textit{et al.} (1998) suggest that the predominant evolutionary effects are that the distant clusters have a substantial deficit of S0 systems compared to 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 due to 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 the local and distant clusters may result either from an increase the the general level of star formation activity at higher redshift (eg., Lilly \textit{et al.} 1996, Cowie \textit{et al.} 1997), or might result 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 due to its motion relative to the diffuse gaseous intra-cluster 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 disks (Nulsen 1982). These occur even
when the ram-pressure is insufficient to strip the gas disk directly: turbulence in the gas flowing around the galaxy entrains interstellar medium resulting in its depletion.

If ram-pressure or viscous stripping is effective at removing gas, then cluster spirals should have truncated disks deficient in HI. Observational evidence for this is marginal. Some galaxies show clear evidence for stripping, e.g. NGC 4522 (Kenny & Koopmann 1998), UGC 6697 (Nulsen 1982) or several Virgo cluster galaxies (Cayatte 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 virialised clusters of galaxies, since the relative velocity of galaxies is too high for such encounters to be frequent (i.e. 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 dSph's 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 disks are substantially thickened.

A final mechanism that should not be over-looked is the truncation of star formation through the removal of the hot gas reservoir that is thought to surround galaxies (Larson et al. 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 (eg., Kauffmann & Charlot 1998, Baugh et al. 1998); however, it appears unable to adequately reproduce the star formation histories of real cluster galaxies, since the spectroscopic studies require that star formation is suppressed on far shorter timescales (eg., 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 rapidly suppressing the star-formation rate. In particular, we use fully 3 dimensional SPH simulations to compare 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 disk or whether the effects can propagate inwards. It is also of interest to determine the timescale on which the stripping should occur, since 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 3 dimensional simulations c.f. Farouki & Shapiro (1980). Balsara et al. (1994) performed several high resolution simulations of the gas stripping process using an Eulerian code, but again using a restricted 2-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 et al. (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 that gas will be stripped via ram pressure. Techniques and results of numerical SPH simulations are presented in Section 3, which are discussed in Section 4, along with the shortcomings of ram pressure stripping as the mechanism behind explaining 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 disk, halo and bulge components. The bulge is spherical and has a mass density profile of the form:

$$\rho_b(r) = \frac{M_b}{4\pi^2 \alpha (r/r_b)^3}, \quad (1)$$

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

$$\rho_h(r) = \frac{M_h}{2\pi^{3/2} r_1 r_b^{5/2} (1 + r^2/r_1^2)} \exp\left(-r^2/r_1^2\right), \quad (2)$$

where $r_1$ is the core radius, $r_1$ is the truncation radius and $M_h$ is the mass. The mass normalisation requires that the constant:

$$\alpha = 1/\{3 + (1/2) q \exp(q^2)[1 - \text{erf}(q)]\} \quad (3)$$

where $\text{erf}(q)$ is the error function and $q = r_h/r_1$. The disk is axisymmetric and is composed of both stars and gas. Its mass density profile is an exponential of the form:

$$\rho_d(R, z) = \frac{M_d}{4\pi R_d^2 z_d} \exp\left(-R/R_d\right) \text{sech}^2(z/z_d) \quad (4)$$

where $R_d$, $z_d$ and $M_d$ are the cylindrical scale length, the vertical thickness and mass, respectively. We will replace the subscript $d$ by $s$ to refer to the stellar disk, or $g$ to refer to the gaseous disk.

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

3 ANALYTIC SOLUTION

We have applied the ideas of Gunn & Gott (1972) to the galaxy model in order to obtain analytic estimates of the ra-
spect to the ICM and $\rho$ and for the halo, the gas will be stripped.

These authors stated that the gaseous disk will be removed if the ram pressure of the ICM is greater than the restoring gravitational acceleration for unit area provided by the galaxy's disk (c.f. Sarazin 1986). In this case, the ram pressure is $P = \rho_{icm} v^2$, where $v$ is the velocity of the galaxy with respect to the ICM and $\rho_{icm}$ 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, $\phi$, of the galaxy can be obtained 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,

$$\frac{\partial \phi_b}{\partial z}(R, z) = \frac{GM_b}{(r + R)^2} \frac{z}{r}$$

and for the halo,

$$\frac{\partial \phi_h}{\partial z}(R, z) = \frac{2\alpha GM_h}{\pi^{1/2} r^2} \int_0^{\pi/\alpha} \frac{x^2 \exp(-x^2)}{x^2 + q^2} dx.$$  

The analytical solution of the Poisson equation for the disk 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 disk with a surface density

$$\sigma_d(R) = \int_{-\infty}^{\infty} \rho_d(R, z) dz = \frac{M_d}{2 \pi R_d} \exp(-R/R_d).$$

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

$$\frac{\partial \phi_d}{\partial z}(R, z) = GM_d \int_0^{\infty} \frac{J_0(kR) \exp(-k|z|)}{[1 + (kR_d)^2]^{3/2}} dk.$$  

Figure 1. 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.

$$J_0(x) = \int_0^\pi \cos(x \sin \theta) d\theta$$

is the Bessel function of the first kind of order zero. The stripping radius $R_{str}$, can then be computed by solving the equation

$$\frac{\partial \phi}{\partial z}(R, z) \sigma_g(R) = \rho_{icm} v^2,$$  

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 Figure 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 realisation. The agreement between the analytical estimates (solid curved line) and the envelope of values computed from the particles (dots), demonstrate the validity of using Equation 8.

The ram-pressure values for 2 different ICM densities and relative velocities are shown as horizontal lines in Figure 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 disk, $R_{str}$, 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 $R < R_{\text{stp}}$, the restoring gravitational force per unit mass is greater than the ram-pressure and the gas remains bound to the galaxy. On the contrary, for $R > R_{\text{stp}}$ the ram-pressure overcomes the gravitational force and the gas can be stripped.

Figure 2 demonstrates that the main contribution to the total restoring gravitational force comes from the stellar disk, although in the central parts of the galaxy the bulge becomes important. For this model, the bulge contributes 30% of the disk 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 $R_{\text{stp}}$ 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 4 subsamples according to the shape of the surface brightness profile and conclude that ram-pressure is the main reason of gas removal in subsample III (3 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 $\rho_{\text{icm}} = 0.1\rho_C$ and $v = 1000$ km s$^{-1}$, with different values of the galaxy’s scale length $R_d$. In order to compare directly with the observations we define an “optical” radius $R_o$ as the size of the stellar disk. Then, we scale linearly from $R_d$ to $R_o$. For $R_d = 3.5$ kpc this value is $R_o = 24$ kpc and at this position the density has decreased by a factor $\sim 10^{-3}$. In Figure 3 we show the ratio of the stripping radius to “optical” radius $R_{\text{stp}}/R_o$ 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

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

Ideally, gas particles will flow onto the disk, imparting a significant fraction of their momentum as their motion is halted by the disk gas. Too hot to accrete onto the disk, they will be forced to flow around and re-join the ICM. To achieve this spatial resolution, the ICM particles should have a mass that is at least as small as that of the disk 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 $r_A = 1.5h^{-1}\text{Mpc}$ for the Coma cluster is $M_{\text{icm}} = 5 \times 10^{13}h^{-5/2}\text{M}$ (White et al. 1993). On the other hand, the $H_I$ component of a massive galaxy is $M_{H_I} \sim 10^{10}\text{M}$ (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 disk like nuclear explosions leaving large holes and creating a large artificial drag. To suppress this effect, a minimum ICM gas mass equal to the disk 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 $\rho_{\text{icm}}$ 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 $R_{\text{cyl}} = 30$ kpc and thickness $z_{\text{cyl}} = 10$ 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.

<table>
<thead>
<tr>
<th>$N$</th>
<th>$M_{\text{total}}$</th>
<th>$m_p$</th>
<th>$[L]$ kpc</th>
<th>$\epsilon$ kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICM</td>
<td>16000</td>
<td>0.24</td>
<td>1.47e-5</td>
<td>0.75</td>
</tr>
<tr>
<td>Disk(gas)</td>
<td>8000</td>
<td>1.12</td>
<td>1.40e-4</td>
<td>3.5 0.35</td>
</tr>
<tr>
<td>Disk(stars)</td>
<td>8000</td>
<td>4.48</td>
<td>5.60e-4</td>
<td>3.5 0.35</td>
</tr>
<tr>
<td>Bulge</td>
<td>2500</td>
<td>1.68</td>
<td>6.72e-4</td>
<td>0.5 0.21</td>
</tr>
<tr>
<td>Halo</td>
<td>8000</td>
<td>21.28</td>
<td>2.66e-3</td>
<td>3.5 24.5</td>
</tr>
<tr>
<td>Total</td>
<td>42500</td>
<td>28.58</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. The main parameters of each component of the model spiral galaxy. $N$ is the number of particles. $M_{\text{total}}$ 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) and $m_p$ is the mass per particle for each component, all expressed in units of $10^{10}M_\odot$. $[L]$ is the characteristic length scales of the different components (for the disk we quote $R_d$ and $z_d$; for the halo we quote $r_h$ and $r_1$). $\epsilon$ is the gravitational softening.
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 $N_{\text{ICM}} = 16000$ gas particles inside the cylinder ($N_{\text{ICM}} = 20000$ for the box) with a density $\rho_{\text{icm}}$ 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 $\rho_{\text{icm}} = \rho_C \equiv 5.64 \times 10^{-27} h_{50}^3 \, \text{g cm}^{-3}$ (Briel, Henry & Bohringer 1992) to the density of a cluster like Virgo $\rho_{\text{icm}} = 0.1 \, \text{pc}$. (Throughout this paper we have adopted a value of the Hubble constant of $H_o = 50 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$).

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 $z_{\text{cyl}}/2$, is re-entered at $-z_{\text{cyl}}/2$. We also apply reflecting boundaries conditions for particles that leave the cylinder edges at $x^2 + y^2 = R_{\text{cyl}}^2$. In Table 2 we list the main characteristics of the simulations. The code has individual timesteps that are typically $\approx 10^4$ years and we run each simulation for more than $10^5$ years.

In Figure 4 and 5 we show the projected distribution of disk 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, 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 Figure 6 we show the evolution of the radius $R_{\text{stp}}$, and the fraction of gas mass that remains inside this radius. We estimate $R_{\text{stp}}$ as the radius of the most distant gaseous disk particle from the center, and the mass is calculated using the disk particles inside a cylinder of radius $R_{\text{cyl}}$ 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 Figure 7 we have plotted the stripping radius, $R_{\text{stp}}$, as function of the velocity $v$ of the ICM. The curves show the analytical solution of equation 9 for different values of density: $\rho_{\text{ICM}} = 0.1 \rho_C$ (dotted line), $\rho_{\text{ICM}} = \rho_C$ (solid line) and $\rho_{\text{ICM}} = 10.0 \rho_C$ (dashed line). For each ICM density, the upper curve shows the solution taken into account the restoring gravitational force of all components of the galaxy, and the lower corresponds to including just the stellar disk. The solid 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 edge-on. We also show as solid circles the observational radius from Cayatte et al. (1993) for 3 galaxies in the Virgo cluster, assigned a velocity of 1200 km s$^{-1}$.
Evolution of the radius and mass of the gas disk as a function of time. Both rapidly converge on a timescale $\sim 5 \times 10^7$ years. 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 $\rho = 0.1 \rho_{\text{coma}}$ and $\rho = 1.0 \rho_{\text{coma}}$. The short and long dashed lines are for the edge-on and 45° simulations with a velocity of 2000 km s$^{-1}$ and $\rho = 1.0 \rho_{\text{coma}}$.

The size of the stripped gas disk, $R_{\text{stp}}$, 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.

### Table 2

<table>
<thead>
<tr>
<th>Run</th>
<th>$\rho/\rho_C$</th>
<th>$v$ [km/s]</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0</td>
<td>0</td>
<td>isolation</td>
</tr>
<tr>
<td>B</td>
<td>0.1</td>
<td>1000</td>
<td>face-on</td>
</tr>
<tr>
<td>C</td>
<td>0.1</td>
<td>2000</td>
<td>face-on</td>
</tr>
<tr>
<td>D</td>
<td>0.1</td>
<td>3000</td>
<td>face-on</td>
</tr>
<tr>
<td>E</td>
<td>1.0</td>
<td>1000</td>
<td>face-on</td>
</tr>
<tr>
<td>F</td>
<td>1.0</td>
<td>2000</td>
<td>face-on</td>
</tr>
<tr>
<td>G</td>
<td>1.0</td>
<td>3000</td>
<td>face-on</td>
</tr>
<tr>
<td>H</td>
<td>1.0</td>
<td>2000</td>
<td>edge-on</td>
</tr>
<tr>
<td>I</td>
<td>1.0</td>
<td>2000</td>
<td>45°</td>
</tr>
</tbody>
</table>

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 galaxies’ star formation rates. A general decline is expected since galaxies in the cluster will gradually consume the gas in their disks, and the possible sources of replenishment, such as HVC’s or gas rich satellites, will be stripped away. However, a slow decline is not adequate to explain the the strong Balmer absorption line spectra frequently seen in the cluster galaxies (Couch & Sharples, 1987, Barger et al., 1995). 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 et al. 1998), although these process 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 due to the ICM causes a substantial reduction in the size of gaseous disks. Indeed, Bothun & Dressler (1986) find several star-bursting, HI deficient spirals in the core of the Coma cluster. The timescale 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:

- The largest deficit of this model is that in no case is the gas disk completely removed. A substantial portion of the cold gas remains sufficiently bound to the stellar disk 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 disk is truncated at ~ 1.5 disk scale lengths. 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 2. In lower density environments, the effect is much lower: stripping the disk beyond 3 scale lengths reduces the star formation rate by only 10%. Fujita & Nagashima (1998) recently examined the colour evolution of spiral galaxies that have suffered ram-pressure stripping with similar conclusions.

- Several authors find that the star-formation rate in cluster galaxies is significantly reduced between the field and the cluster center (Dressler et al. 1997, Balogh et al. 1998, Poggianti et al. 1998). Even when the diffuse gaseous material is stripped from the disk, additional gas will remain in the form of dense molecular clouds. These cannot be removed by the ram-pressure force since 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).

- 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) demonstrate that 20% of cluster galaxies orbit with apocenter to pericenter ratios larger than 10:1. Thus, 20% of galaxies that have orbited through the core of the Coma cluster may be found at, or beyond, the virial radius. Nevertheless, to fully explain this effect we require a mechanism that is effective in environments less dense than the core of the Coma cluster.

- 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 substantially compress the leading edge of the disk. 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 star-bursts 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 generalised to explicitly include 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 disk. Secondly, tidal shocks via galaxy harassment may tend to make the disk 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 due to 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 analyze the ram-pressure stripping process of a spiral galaxy passing through the ICM using hydro-dynamical simulations and we conclude that:

- 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 $\rho v^2$ to the restoring force provided by the disk, as originally suggested by Gunn & Gott (1972).

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

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

- Disks moving through clusters with orbital inclination edge on to the direction of motion lose about 50% less gas than a full face on encounter with the ICM.

- Observations of the H$\alpha$ distribution in cluster spirals show evidence for tidally truncated disks by an amount roughly in accordance with analytic expectations.

- Ram pressure stripping alone does not provide the physical mechanism behind the origin of the Butcher-Oemler effect.
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