Gone with the wind: The origin of S0 galaxies in clusters

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We present the first 3-dimensional high resolution hydro-dynamical simulations of the interaction between the hot ionised intra-cluster medium and the cold interstellar medium of spiral galaxies. Ram pressure and turbulent/viscous stripping removes 100% of the atomic hydrogen content of luminous galaxies like the Milky Way within 100 million years. These mechanisms naturally account for the morphology of S0 galaxies, the rapid truncation of star formation implied by spectroscopic observations, as well as a host of observational data on the HI morphology of galaxies in clusters.

Crucial observational evidence for the hierarchical formation of structure in the universe is the dramatic evolution of galactic morphologies in dense environments over the past 5 billion years (1,2). The key puzzle that remains to be solved is the origin of the large population of lenticular (S0) galaxies found in nearby clusters (3,4). These featureless disky galaxies contain no atomic gas and show no signs of recent star-formation (3).

The Hubble Space Telescope revolutionised our view of the universe by revealing that distant galaxies appeared different from the local population. In contrast to local clusters, high resolution imaging of distant clusters led to the spectacular finding that young clusters of galaxies are filled with spiral galaxies (2,4,5) and contain almost no lenticular (S0) galaxies, whereas the ratio of luminous ellipticals to lenticulars (S0) increases by a factor of five between a redshift z=0.5 and the present-day (3). S0’s can be characterised by their thick featureless disks that show no evidence for recent star-formation and the increase in their population appears to be countered by a similar decrease in the number of luminous late-type spirals in clusters. The data suggest that a transformation between these galaxy types is taking place as a direct consequence of the cluster environment.

Three mechanisms have been proposed that can lead to morphological transformation between galaxy classes. Mergers will transform disks to spheroidals (6,7), but are only effective in low density environments (8). Gravitational tidal interactions between cluster galaxies can naturally account for the observed evolution of the faint end of the luminosity function and the transformation of small disks to faint spheroidals (8). However, more massive bulge dominated systems are stable to tidal disruption (10).

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the resulting disk thickening from tidal heating suppresses spiral features and causes a morphological similarity to S0's, neither of these two processes suppress star-formation.

In addition to disk thickening, a mechanism that actively extinguishes star-formation is crucial since the stellar populations of S0 galaxies are old and their spectra indicate that star-formation was abruptly halted several billion years ago (11,12,13). A slow decline in the star formation rate, such as expected from the exhaustion of a reservoir of cold gas, is unable to explain the strongly enhanced Hydrogen absorption lines seen in many distant cluster galaxies.

A candidate mechanism was proposed by Gunn & Gott (14) over two decades ago. Their simple force-balance estimates suggested that the motion of galaxies through the hot ionised intra-cluster medium (ICM) creates a “ram-pressure” that could potentially strip away significant amounts of gas from disks. However, a full description of this mechanism must include complex turbulent and viscous stripping (15) at the interface of the cold and hot gaseous components as well as the formation of bow-shocks in the ICM ahead of the galaxy. Although these processes have been cited over 1000 times in the literature, their effectiveness and efficiencies have received little theoretical investigation.

The ram pressure is proportional to $\rho_{ICM}v_{gal}^2$, therefore the infalling galaxy suffers most gas loss at its pericentric passage, where its velocity can be as large as 3000 km s$^{-1}$ and the intra-cluster gas density approaches 3000 $h_{50}^{1/2}$ atoms m$^{-3}$. Gunn & Gott’s (14) order of magnitude estimates suggest that the typical gas disk would be stripped down to $\sim$ 5 kpc, a radius confirmed by smoothed particle hydro-dynamic simulations that follow just the ram pressure process (16). However, this leaves 50% of the original HI confined in the disk which would continue to form stars for several billion years. Although this is a significant reduction in the star formation rate, it does not explain the absence of any recent star formation in cluster S0 galaxies.

We have performed the first high resolution three dimensional numerical simulations of these hydro-dynamical processes to accurately address the efficiency of stripping and the timescale on which it occurs. Previous work has been either in 2D with spherical galaxy models (17,18), or in 3D using a code that could not model viscosity and turbulence (16). Our parallel computer code (19) uses high-resolution shock-capturing techniques to follow the fluid dynamic equations allowing us to observe the full complexity of the ram-pressure and turbulent/viscous stripping processes. We can also follow the shocks that penetrate the interstellar medium (ISM) and ICM and the thermo-dynamical evolution of the ICM and stripped galactic gas. Because it is fully three dimensional, our code is not forced to preserve the cylindrical symmetry of the galaxy (18).

We construct a self-consistent equilibrium model galaxy with stellar disk and bulge components designed to resemble a luminous spiral similar to the Milky Way or An-
The stars are embedded within a dark matter halo constructed such that the total rotational velocity of the disk is a constant \(220\ \text{km s}^{-1}\) \((20)\). The real ISM is complex gaseous medium formed by a cold diffuse HI component and dense molecular clouds (MC) with temperatures \(T_{MC} \sim 10^2\ \text{K}\). The diffuse gaseous disk is constructed by specifying the density, and velocity at each grid cell according with \((20)\), and constant temperature \(T_{ISM} = 10^4\ \text{K}\) – the lower threshold in our simulations. The MC’s are typically three order of magnitude denser than the HI component and have sizes of the order of several parsecs. Even though our numerical code is highly optimised and is running on state of the art parallel hardware, the maximum resolution that we can achieve is \(\sim 100\) parsecs, therefore we cannot resolve individual MC’s in our simulations. However, MC’s are so small and dense that they will remain unaffected by the stripping processes \((21)\). Initially, the ICM is considered as an uniform medium with constant density and temperature \(T_{ICM} = 10^8\ \text{K}\). Both the ICM and ISM are treated as ideal fluids with adiabatic exponent \(\gamma = 5/3\). Their evolution is described by the hydrodynamic equations that are integrated using the numerical techniques described above. The stellar and dark matter components are evolved using an N-body Particle-Mesh code. All components are coupled gravitationally through Poisson’s equations which is solved using a fast 3D FFT method. No cooling has been considered since the timescales are so short \((24)\). At our best (standard) resolution we use \(512^3(256^3)\) cells across a cubic region centered on the galaxy with length 64 kpc, thus our nominal resolution is \(\sim 100(200)\) parsecs.

We have simulated different infall geometries, velocities and ICM gas densities and ISM structure \((23)\). Two of these simulations are pictured in Figure 1, which show a galaxy moving face on and nearly edge on through the core of a rich cluster like Coma – \(\rho_{ICM} = 2.6 \times 10^3\ h_{50}^{1/2}\ \text{atoms m}^{-3}\) – at a velocity of 2000 km s\(^{-1}\). We plot only the ICM and ISM components of the simulation to highlight the gas dynamical processes - the stellar disk remains unperturbed. The outer gas disk of the infalling galaxy is rapidly stripped away and forms trailing streams of warm HI in pressure equilibrium with the ICM. Turbulence and viscous stripping ablate the gas disk even further \((24)\).

We find a rich structure of shocks. The most obvious is the prominent curved bow shock that propagates through the ICM ahead of the galaxy, heating the ICM from a temperature of \(10^8\) to \(5 \times 10^8\) degrees \((23)\). A complex series of cross shocks occur in the rarefied hot medium behind the galaxy, which may be visible as a wake of enhanced X-ray emission \((25)\). Although not apparent on this scale, a second shock is driven through the ISM of the galaxy, raising the internal pressure by over two orders of magnitude. The efficiency and time scale of star formation are strong functions of the ambient ISM pressure \((27)\). As the shock propagates through the galaxy, it may promote the collapse of molecular clouds, briefly enhancing the galaxy’s star formation rate.

Whereas previous work treated the ISM as a smooth disk of HI, in reality, the ISM
has complex multi-phase structure, filled with bubbles, shells and holes ranging in size from a few parsecs to a kpc \(^{(27)}\). Furthermore, the inner couple of kpc of most bright spiral galaxies are extremely deficient in HI. The nearest and best studied galaxy is Andromeda which has over 100 HI holes and a central region of radius 2 kpc devoid of neutral gas \(^{(28)}\). Our simulations show that this structure makes the disk much more susceptible to viscous stripping. As the ICM streams through these holes, it ablates their edges and prevents stripped gas falling back on to the centre of the galaxy. This is an important difference between previous work that claimed significant replenishment from stripped material. When we model our disk on Andromeda’s we find that these processes lead to the removal of the entire diffuse HI component on a timescale of 100 million years. Even if the HI holes contain a large quantity of molecular hydrogen locked within MC’s, due to their small covering factor they would not affect the removal of the HI component of the gaseous disk \(^{(21)}\). Combined with galaxy harassment, this process has all the properties required to explain the rapid transformation between spiral and S0 galaxies seen in distant clusters.

It is important to stress that the effectiveness of ram-pressure stripping does not depend on the galaxy moving face-on through the ICM. We find that galaxies inclined twenty degrees to the direction of motion suffer as much stripping as face on encounters. Since the orientation of the disk remains fixed as the galaxy orbits through the cluster, a galaxy moving edge on at first pericentric passage is likely to be inclined to the direction of motion at some other point of its orbit \(^{(29)}\). Only a small fraction of galaxies will orbit with their disks aligned exactly with the orbital plane.

The timescale for stripping is very short compared to the orbital timescale, therefore galaxies will only rarely be observed at the moment of stripping. Evidence for ongoing ICM/ISM interaction may be found by observing compression of the leading contours of disk HI emission, and wings or tails of HI behind the galaxy \(^{(30,31)}\). In Figure 3 (see also \(^{(32)}\)) we compare two recent and striking examples of these processes with snapshots of our simulations, showing that the observed morphologies are well reproduced. After passage through the cluster, disks will be either HI deficient compared to field spirals, or they may lack neutral hydrogen altogether. Galaxies in this latter class would subsequently be identified as S0’s. HI maps of galaxies in the Virgo and Coma clusters show few galaxies with any HI, although some galaxies in the outer parts of the cluster are extremely HI deficient \(^{(33,34,35)}\). The efficiency of stripping explains why such galaxies are so rare.

Our simulations demonstrate the importance and effectiveness of the ram-pressure and transport processes. The interaction between the ICM and ISM removes the entire HI component as well as any diffuse reservoir of hot gas within its dark matter halo. But what happens to the molecular clouds in the infalling galaxy? These clouds are so dense and small that they cannot be removed by the ram-pressure of the ICM and are
not resolved in our simulation. To understand the fate of the molecular gas we need to consider the cycle of star formation in a little more detail. In a quiescent field galaxy, molecular clouds are continually being disrupted by the star clusters formed within them and they are subsequently reformed from the ambient diffuse HI. Within clusters, galaxies are swept clear of HI and this cycle is broken: the disruption of the clouds is not balanced by the condensation of new self-shielding molecular complexes. Current models suggest the lifetime of large molecular clouds is less than a few tens of millions of years (27,36). We would therefore expect the ram pressure to lead to a decline in star formation on the same timescale as the disruption of the molecular clouds. This scenario predicts that cluster S0 galaxies will not contain molecular gas (37).

Furthermore, the pressure increase in the ISM may create a burst of star-formation, as the counter shock compresses existing molecular clouds within the galaxy (38). This would explain the prevalence of strongly enhanced Hydrogen absorption lines in many distant cluster S0 galaxies, and is supported by the spectacular H\(\alpha\) emission seen from several nearby galaxies as they are stripped (39,40).

This mechanism leads to a population of post-starburst S0 galaxies, preferentially populating the central regions of rich clusters. However, ram-pressure is not the only effect at work in clusters of galaxies. Longer timescale processes, such as stellar evolution, tidal forces and ‘harassment’ tend to thicken the stellar disk and enhance the relative importance of the galaxy’s bulge. Taken together, these processes can explain the remarkable transformation of cluster galaxies and the dramatic evolution in the galaxy populations of dense environments. S0’s in the field most likely form via a minor merger or the accretion of a satellite (7). This formation mechanism is markedly different from what we are proposing in clusters, and suggests that there will be observable photometric, spectral and kinematical differences between field and cluster S0’s.

References and notes

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19. V. Quilis, J.M. Ibáñez, D. Sáez, *Astrophys. J.* **469**, 11 (1996). The numerical code used in this report is a 3D Eulerian code on a fix cartesian grid. This code is based on modern high-resolution shock-capturing (HRSC) techniques, a general denomination for a recently developed family of methods to solve hyperbolic systems of equations such as the hydro-dynamic equations. Our code is similar to PPM (Piecewise Parabolic Method) but with some particular features. It has four key ingredients: i) conservative formulation, numerical quantities are conserved up to the numerical order of the method, ii) the reconstruction procedure, which allow to recover the distribution of the quantities inside the computational cells, iii) the Riemann solver, which solves the evolution of discontinuities between cell interfaces, and iv) the advancing in time, designed to be consistent with the conservation properties. HRSC schemes have the following advantages; they do not suffer from numerical artifacts such as artificial viscosity, they can resolve strong shocks extremely well – typically in one or two cells, strong gradients are perfectly modelled, they work very well in low density regions and are high-order in smooth regions of the flow.

20. We construct the galaxy following the Hernquist’s model [L. Hernquist, *Astrophys. J. Suppl.* **86**, 389 (1993)]. Four components are considered: (i) Stellar bulge,

\[ \rho_b(r) = \frac{M_b}{2\pi r_b^2} \frac{1}{r(1 + \frac{r}{r_b})^3}, \]

with \( r_b = 0.5 \) kpc, \( M_b = 1.7 \times 10^{10} \, M_\odot \). (ii) Dark matter halo,

\[ \rho_h(r) = \frac{M_h}{2\pi^{3/2} r_b^{5/2}} \left(1 + \frac{r^2}{r_h^2}\right)^{-\alpha}, \]
with \( r_h = 3.5 \text{ kpc}, r_t = 24.5 \text{ kpc}, M_h = 26.5 \times 10^{10} \text{ } M_\odot, \alpha = 1/[1 - \pi^{1/2}q e^{q^2}[1 - \text{erf}(q)] \) being \( \text{erf}(q) \) the error function with \( q = r_h/r_t \). (iii) Stellar disk, 

\[
\rho_s(R, z) = \frac{M_s}{4\pi R_s^2 z_s} \exp(-R/R_s) \text{sech}^2(z/z_s),
\]

where \( R_s = 3.5 \text{ kpc}, z_s = 0.35 \text{ kpc}, M_s = 5.6 \times 10^{10} \text{ } M_\odot \). (iv) Gas disk, 

\[
\rho_g(R, z) = \frac{M_g}{4\pi R_g^2 z_g} \exp(-R/R_g) \text{sech}^2(z/z_g),
\]

being \( R_g = 3.5 \text{ kpc}, z_g = 0.35 \text{ kpc}, M_g = 1.4 \times 10^{10} \text{ } M_\odot \). The total masses of the different components are \( 5 \times 10^{10} \text{ } M_\odot, 1.7 \times 10^{10} \text{ } M_\odot \) and \( 5 \times 10^9 \text{ } M_\odot \) for the disk of stars, bulge, and gaseous disk, respectively. \( 10^5 \) and \( 1.4 \times 10^5 \) particles are used to describe the DM halo and the stellar components respectively.

21. Molecular clouds are structures much smaller than the maximum numerical resolution that we can achieve (100 parsecs). Therefore, they cannot be modelled in our simulations as components of the ISM which it is described as exponential disk of cold HI. Nevertheless, we can conclude that MC’s are not relevant to the ram-pressure stripping suffered by the HI component due to their small size and high density. Several previous studies, such as A.C. Raga, J. Cantó, S. Curiel, S. Taylor, Mon. Not. R. Astr. Soc., 295, 738 (1998) (and references therein) justify this statement. In this paper, the authors carried out an analytical and numerical study of the interaction of MC’s with winds. If we apply their conclusions to the typical parameters adopted here, the clouds would remain unaltered, that is, MC’s do not suffer ram-pressure stripping by the interaction with the ICM. A second possible effect of MC’s embedded in the flow is to shield the HI component from the ICM. This effect is also negligible due to the small covering factor of MC’s. Their cross-sections is less than 1% of the area of one of our numerical cells, thus they would act like single points in a fluid.

22. The ISM is heated very efficiently by shocks to a temperature \( T_{\text{ISM}} = 10^6 \) in a very short timescale. However, the cooling time for the ISM material with typical metal abundance is much shorter than the dynamical timescale. A good approximation is that all the energy imparted into the ISM via shocks is immediately re-radiated away, possibly as \( H_\alpha \) photons.

23. We have carried out a set of simulations setting different values for the ICM parameters, orientation of the galaxy against the wind, and the composition of the ISM. Two ICM densities have been considered \( 0.1 \rho_{\text{coma}} \) and \( \rho_{\text{coma}}(\rho_{\text{coma}} = 2.6 \times 10^{3} h_{50}^{1/2} \text{ atoms m}^{-3}) \). The ICM velocities used were \( 1000 \text{ km s}^{-1} \) and \( 2000 \text{ km s}^{-1} \). The orientation of the galaxies moving through the wind were varied from face-on
to edge-on, passing through 45 and 20 degrees. We use three ISM compositions:
1) uniform smooth exponential disk (20). 2) The previous disk but with a central
region devoid of diffuse HI gas with a 2 kpc radius. 3) The original exponential disk
in which ten small holes each of radius 300 parsecs are randomly located within a 5
kpc radius from the center, and in the same region the local density of the cells is
randomly increased by a factor of two with a 50% probability. This last case pre-
tends to resemble an inhomogeneous ISM. All of the simulations show a rapid loss
of gas but the models with $\rho_{ICM} = 0.1\rho_{coma}$, $v_{ICM} = 1000 \text{ km s}^{-1}$ and no holes, are
not able to remove the bulk of this material. Simulations with high ICM velocity
and density but with a smooth ICM with no holes retain small HI disk with sizes of
3 kpc after 100 Myrs. The more realistic cases including a non-uniform ISM exhibit
massive gas losses with almost no HI component remaining after 100 Myrs. Only
the strict edge-on cases are weakly affected by the stripping processes, but this con-
figuration for several orbits is expected to be quite rare. Results of one simulation
including ten small holes and inhomogeneous density are shown as mpeg movies in
http://www.scienceonline.org.

24. Ram pressure stripping removes the outer disk gas in a timescale of 20 Myrs. Tur-
bulence and viscous stripping operate over the entire surface of the disk and are
effective at removing the diffuse HI even from regions of the disk that are above
the threshold for ram pressure effects. These latter processes operate over a longer
timescale and are effective at depleting the diffuse HI from the central disk in a
timescale of order of the crossing time for the ICM through the ISM (see Figure 2).

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29. It is important to stress the process described in this report can be very effective
at modifying galactic morphologies throughout clusters. Following the results in
(8) who determined the average galaxy orbit in clusters, we have estimated that
more than 90% of galaxies within a rich virialised cluster can be completely stripped
of their diffuse HI. This calculation relied on the facts that: i) the typical time
scale of the stripping is very short compared with the orbital characteristic time of a
galaxy in cluster $\sim 10^8$ years, ii) even for galaxies moving with a relative angle of
20 degrees to the ICM, all the gas is stripped (see Figure 1), and iii) the form of the
galactic orbits – typically with pericenters less than 500 kpc and an average relation
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37. If the lifetimes of dense molecular clouds are as short as $10^7$ years, then the decline in the molecular gas content of infalling galaxies is as rapid as the rate of HI removal by the stripping process. Initially, this seems at odds with the observations of J.D.P. Kenney and J.S. Young, Astrophys. J., 344, 171 (1989), who found that bright HI deficient spirals in the Virgo cluster contained similar masses of molecular hydrogen to counter-parts of the same morphological type in the field. This apparently suggests that molecular clouds must have a lifetime that is considerably longer than the stripping timescale. However, we note that this comparison is made at a fixed morphology. Morphology is strongly dependent on the star formation rate, in the sense that galaxies with low star formation rate will be classified as earlier type. Thus it is unlikely that galaxies with similar morphology will exhibit large differences in CO content. Rather a large deficiency in CO will result in a galaxy with low star formation rate, and earlier morphological type. It is then hard to disentangle any deficiency in CO content due to stripping from the reduction in CO content expected for the change in morphological type. It is encouraging, nevertheless, that galaxies of earlier type match more closely the curve in Kenney and Young’s data expected if the molecular and atomic gas contents decline at similar rates.

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FIGURES CAPTIONS

Figure 1  The evolution of the gaseous disk of a spiral galaxy moving face on (left column) and inclined 20 degrees to the direction of motion (right column) through a diffuse hot intra-cluster medium. Each snapshot shows the density of gas ($\delta = \rho/\rho_{ICM}$) within a 0.2 kpc slice through the center of the galaxy and each frame is 64 kpc on a side. Note how rapidly the disk material is removed - within 100 million years 100% of the HI is lost. We do not show the stellar disk, bulge or dark matter halo which remain unaffected by the loss of the gaseous component. The box size is 64 kpc and the hydro grid has $256^3$ cells.

Figure 2  Mass loss as a function of time for the model including ten little holes and inhomogeneous density. We plot the evolution of the gaseous mass within a cylindrical slice of 25 kpc radius and thickness 2 kpc centred on the center of mass of the stellar disk. Initially, ram-pressure stripping dominates the gas loss process and the entire outer disk is removed in a very rapid timescale. Viscous and turbulent stripping operates continuously, but over a longer timescale, resulting in a roughly linear rate of mass loss. We stop this simulation after 130 million years by which time 97% of the gas disk has been removed.

Figure 3  Observational evidence (left panels) for ram-pressure processes compared with our hydro-dynamical simulations at different epochs (right panels). The first panel shows a HI map of NGC 7421 which shows wings of gas being pushed back by its motion through a diffuse ionised medium \cite{31}. The second panel shows the HI deficient galaxy NGC 4548 orbiting in the Virgo cluster \cite{30}. The remaining gas has a ring-like morphology very similar to our simulation after 50 million years.

Next Figures would be shown in http://www.scienceonline.org as an extra material

Figure 4  Observational evidence (left panels) of trails of gas compared with our simulations at different epochs (right panels). The first panel shows the radio continuum (contours) brightness distribution superposed over a gray scale representation of H intensity in galaxy 97073 in cluster A 1367 (see Figure 1a in \cite{39}). The second panel shows spectacular radio jets that have been swept backwards for tens of kpc by motion of the galaxy through the ICM of a rich cluster at $z=0.3$ (radio data courtesy of R. Ivison, A.W. Blain and I. Smail). Note that the radio emission may be unrelated to the stripping process, but the morphological appearance is very similar to the trails of stripped gas in our simulations.
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