Gone with the Wind: The Origin of S0 Galaxies in Clusters

Vicent Quilis, Ben Moore, Richard Bower

We present three-dimensional, high-resolution hydrodynamical simulations of the interaction between the hot ionized intracluster medium and the cold interstellar medium of spiral galaxies. Ram pressure and turbulent/viscous stripping remove 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 and the rapid truncation of star formation implied by spectroscopic observations, as well as a host of observational data on the neutral hydrogen (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 revolutionized 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 5 between a redshift $z = 0.5$ and the present day (2). S0s can be characterized 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 (9). However, more massive bulge-dominated systems are stable to tidal disruption (10). Although the resulting disk thickening from tidal heating

Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK.

E-mail: vicent.quilis@durham.ac.uk (V.Q.); ben.moore@durham.ac.uk (B.M.); r.g.bower@durham.ac.uk (R.B.)

suppresses spiral features and causes a morphological similarity to S0s, neither of these two processes suppress star formation.

In addition to disk thickening, a mechanism that actively extinguishes star formation is crucial because the stellar populations of S0 galaxies are old and their spectra indicate that star formation was abruptly halted several billion years ago (11–13). 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 and Gott (14) over two decades ago. Their simple force-balance estimates suggested that the motion of galaxies through the hot ionized intracluster medium (ICM) creates a "ram-pressure" that could potentially strip away substantial 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 more than 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 intracluster gas density approaches 3000 $h_{50}^{1/2}$ atoms m^{-3}. Gunn and Gott's (14) order of magnitude estimates suggest that the typical gas disk would be stripped down to ~5 kpc, a radius confirmed by smoothed particle hydrodynamic 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 substantial 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 (3D) numerical simu-

lations of these hydrodynamical processes to accurately address the efficiency of stripping and the time scale 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 thermodynamical evolution of the ICM and stripped galactic gas. Because it is fully 3D, 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 Andromeda. The stars are embedded within a dark matter halo constructed such that the total rotational velocity of the disk is a constant 220 km s^{-1} (20). The real ISM is a complex gaseous medium formed by a cold diffuse HI component and dense molecular clouds (MC's) with temperatures $T_{MC} \sim 10^2$ K. The diffuse gaseous disk is constructed by specifying the density, and velocity at each grid cell according with (20), and constant temperature $T_{ISM} = 10^4$ 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 optimized and is running on state of the art parallel hardware, the maximum resolution that we can achieve is ~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 a uniform medium with constant density and temperature $T_{ICM} = 10^8$ 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 equation which is solved using a fast 3D FFT method. No cooling has been considered because the time scales are so short (22). 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 ~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 Fig. 1, which shows a galaxy mov-

ing face-on and nearly edge-on through the core of a rich cluster like Coma — $\rho_{ICM} = 2.6 \times 10^3$ $h_{50}^{1/2}$ 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 5×10^8 degrees (25, 26). 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 multiphase structure, filled with bubbles, shells, and holes ranging in size from a few parsecs to a kiloparsec (27). Furthermore, the inner couple of kiloparsecs 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 center 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 time scale of 100 million years (My). Even if the HI holes contain a large quantity of molecular hydrogen locked within MC's, because of 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 20° to the direction of motion suffer as much
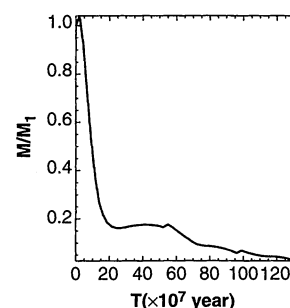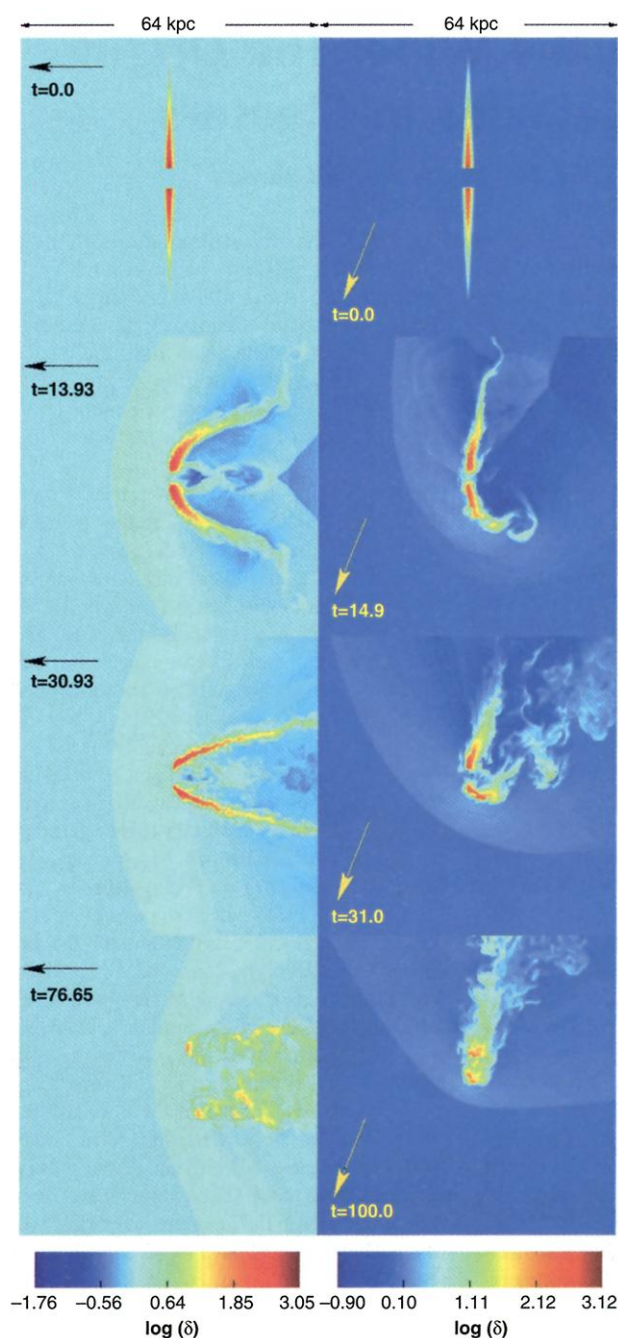
stripping as face-on encounters. Since the orientation of the disk remains fixed as the galaxy orbits through the cluster, a galaxy moving edge-on at first pericentric passage is likely to be inclined to the direction of motion at some other point of its orbit (29). Only a small fraction of galaxies will orbit with their disks aligned exactly with the orbital plane.

The time scale for stripping is very short compared to the orbital time scale, 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 Fig. 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 HI 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 (33–35). The efficiency of stripping explains why such galaxies are so rare.

Fig. 1 (left). The evolution of the gaseous disk of a spiral galaxy moving face-on (left column) and inclined 20° to the direction of motion (right column) through a diffuse hot intracluster 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 My, 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. **Fig. 2 (right).** Mass loss as a function of time for the model including 10 little holes and inhomogeneous density. We plot the evolution of the gaseous mass within a cylindrical slice of 25-kpc radius and 2-kpc thickness, centered 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 time scale. Viscous and turbulent stripping operates continuously, but over a longer time scale, resulting in a roughly linear rate of mass loss. We stop this simulation after 130 My, by which time 97% of the gas disk has been removed.

Fig. 3. Observational evidence (left panels) for ram-pressure processes compared with our hydrodynamical 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 ionized medium (*31*). The second panel shows the HI-deficient galaxy NGC 4548 orbiting in the Virgo cluster (*30*). The remaining gas has a ring-like morphology very similar to our simulation after 50 My.
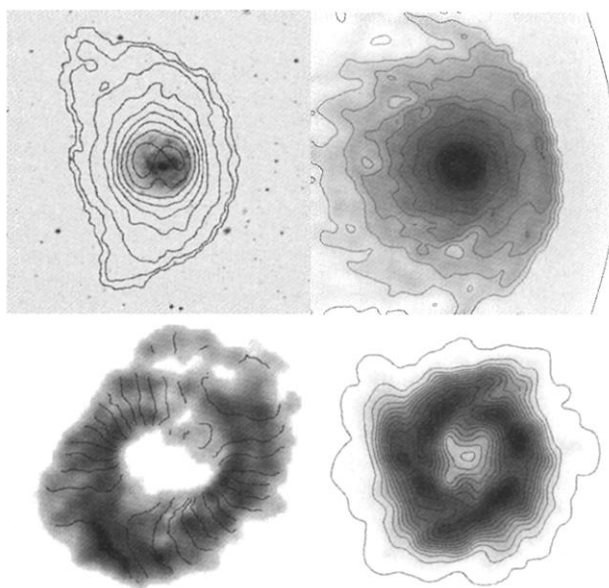
Our simulations demonstrate the importance and effectiveness of the ram-pressure and transport processes. The interaction between the ICM and ISM removes the entire HI component as well as any diffuse reservoir of hot gas within its dark matter halo. But what happens to the molecular clouds in the infalling 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 time scale 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, because 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_α emission seen from several nearby galaxies as they are stripped (*39, 40*).

This mechanism leads to a population of poststarburst 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 time scale 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. S0s 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

1. H. Butcher and A. Oemler, *Astrophys. J.* **285**, 426 (1984).
2. A. Dressler *et al.*, *Astrophys. J.* **490**, 577 (1997).
3. A. Sandage, K. C. Freeman, N. R. Stokes, *Astrophys. J.* **160**, 831 (1970).
4. A. Dressler, *Astrophys. J. Suppl.* **42**, 565 (1980).
5. W. J. Couch, A. J. Barger, I. Smail, R. S. Ellis, R. M. Sharples, *Astrophys. J.* **497**, 188 (1998).
6. A. Toomre and J. Toomre, *Astrophys. J.* **178**, 623 (1972).
7. J. E. Barnes and L. Hernquist, *Astrophys. J.* **471**, 115 (1996).
8. S. Ghigna *et al.*, *Mon. Not. R. Astron. Soc.* **300**, 146 (1998).
9. B. Moore, N. Katz, G. Lake, A. Dressler, A. Oemler, *Nature* **379**, 613 (1996).
10. B. Moore, G. Lake, T. Quinn, J. Stadel, *Mon. Not. R. Astron. Soc.* **304**, 465 (1999).
11. A. Dressler and J. E. Gunn, *Astrophys. J.* **270**, 7 (1983).
12. W. J. Couch and R. M. Sharples, *Mon. Not. R. Astron. Soc.* **229**, 423 (1987).
13. B. M. Poggianti *et al.*, *Astrophys. J.* **518**, 576 (1999).
14. J. E. Gunn and J. R. Gott, *Astrophys. J.* **176**, 1 (1972).
15. P. E. J. Nulsen, *Mon. Not. R. Astron. Soc.* **198**, 1007 (1982).
16. M. G. Abadi, B. Moore, R. G. Bower, *Mon. Not. R. Astron. Soc.* **308**, 947 (1999).
17. T. J. Gaetz, E. E. Salpeter, G. Shaviv, *Astrophys. J.* **316**, 530 (1987).
18. D. Balsara, M. Livio, C. P. O'dea, *Astrophys. J.* **437**, 83 (1994).
19. V. Quilis, J. Mª. Ibánez, 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 hydrodynamic 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: (i) they do not suffer from numerical artifacts such as artificial viscosity, (ii) they can resolve strong shocks extremely well, typically in one or two cells, (iii) strong gradients are perfectly modeled, and (iv) 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,

$$\rho_b(r) = \frac{M_b}{2\pi r_b^2} \frac{1}{\dfrac{r}{r_b}\left(1 + \dfrac{r}{r_b}\right)^3},$$

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

$$\rho_b(r) = \frac{M_h}{2\pi^{3/2}} \frac{\alpha}{r_t r_h^2} \frac{\exp(-r^2/r_t^2)}{(1 + r^2/r_h^2)},$$

with $r_h = 3.5$ kpc, $r_t = 24.5$ kpc, $M_h = 26.5 \times 10^{10} M_\odot$, $\alpha = 1/[1 - \pi^{1/2}q\, e^{q^2}[1 - erf(q)]]$ being $erf(q)$ the error function with $q = r_h/r_t$. (iii) Stellar disk,

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

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

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

being $R_g = 3.5$ kpc, $z_g = 0.35$ kpc, $M_g = 1.4 \times 10^{10} M_\odot$. The total masses of the different components are $5 \times 10^{10} M_\odot$, $1.7 \times 10^{10} M_\odot$, and $5 \times 10^9 M_\odot$ for the disk of stars, bulge, and gaseous disk, respectively. We used 10^5 and 1.4×10^5 particles to describe the DM halo and the stellar components, respectively.
21. MC's are structures much smaller than the maximum numerical resolution that we can achieve (100 parsecs). Therefore, they cannot be modeled 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, and S. Taylor [*Mon. Not. R. Astron. Soc.* **295**, 738 (1998), and references therein] justify this statement. Raga *et al.* 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 are <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 $T_{ISM} = 10^6$ in a very short time scale. However, the cooling time for the ISM material with typical metal abundance is much shorter than the dynamical time scale. A good approximation is that all the energy

imparted into the ISM via shocks is immediately reradiated away, possibly as H_α 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 0.1ρ_{coma} and ρ_{coma} (ρ_{coma} = 2.6 × 10³ $h_{50}^{1/2}$ atoms m^{-3}). The ICM velocities used were 1000 and 2000 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°. We use three ISM compositions: (i) uniform smooth exponential disk (20). (ii) The previous disk but with a central region devoid of diffuse HI gas with a 2-kpc radius. (iii) The original exponential disk in which 10 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 2 with a 50% probability. This last case pretends to resemble an inhomogeneous ISM. All of the simulations show a rapid loss of gas but the models with ρ_{ICM} = 0.1ρ_{coma}, v_{ICM} = 1000 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 My. The more realistic cases including a nonuniform ISM exhibit massive gas losses with almost no HI component remaining after 100 My. Only the strict edge-on cases are weakly affected by the stripping processes, but this configuration for several orbits is expected to be quite rare. Results of one simulation including 10 small holes and inhomogeneous density are shown as mpeg movies at www.sciencemag.org/feature/data/1050370.shl.
24. Ram pressure stripping removes the outer disk gas in a time scale of 20 My. Turbulence 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 time scale and are effective at depleting the diffuse HI from the central disk in a time scale of the order of the crossing time for the ICM through the ISM (Fig. 2).
25. M. R. Merrifield, Mon. Not. R. Astron. Soc. 294, 347 (1998).
26. I. R. Stevens, D. M. Acreman, T. J. Ponman, Mon. Not. R. Astron. Soc. 310, 663 (1999).
27. B. G. Elmergreen and Y. N. Efremov, Astrophys. J. 480, 235 (1997).
28. E. Brinks and E. Bajaja, Astron. Astrophys. 169, 14 (1986).
29. It is important to stress that the process described here can be very effective at modifying galactic morphologies throughout clusters. Following the results in (8) where the average galaxy orbit in clusters was determined, we have estimated that more than 90% of galaxies within a rich virialized 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 to the orbital characteristic time of a galaxy in cluster (~10⁸ years); (ii) even for galaxies moving with a relative angle of 20° to the ICM, all the gas is stripped (Fig. 1); and (iii) the form of the galactic orbits, typically with pericenters <500 kpc and an average relation apocenter:pericenter approximately 6:1, in clusters and all possible orientations respect the ICM.
30. B. Vollmer, V. Cayatte, A. Boseli, C. Balkowski, W. J. Duschl, Astron. Astrophys. 349, 411 (1999).
31. S. D. Ryder, G. Purcell, D. Davis, V. Anderson, Publ. Astron. Soc. Aust. 14, 1 (1997).
32. Indirect evidence for cluster-galaxy hydrodynamic interactions is frequently observed in head-tail radio galaxies with escaping radio-jets that are stripped backwards by the ICM. This long-lived synchrotron emission may arise within the stripped and subsequently ionized plasma that is in pressure equilibrium with the ICM, supported by the original disk magnetic field that is entangled with the stripped disk material [Web fig. 1 (41)].
33. R. H. Warmels, Astron. Astrophys. Suppl. 72, 57 (1988).
34. V. Cayatte, C. Balkowski, J. H. Van Gorkom, C. Kotanyi, Astron. J. 100, 604 (1990).
35. H. Bravo-Alfaro, V. Cayatte, J. H. van Gorkom, C. Balkowski, Astron. J. 119, 580 (2000).
36. L. Blitz and F. H. Shu, Astrophys. J. 238, 148 (1980).
37. If the lifetimes of dense molecular clouds are as short as 10⁷ 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 H to counterparts 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 time scale. 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.
38. Y. Fujita and M. Nagashima, Astrophys. J. 516, 619 (1999).
39. G. Gavazzi et al., Astron. Astrophys. 304, 325 (1995).
40. J. D. P. Kenney and R. A. Koopmann, Astron. J. 117, 181 (1999).
41. Supplementary material is available at www.sciencemag.org/feature/data/1050370.shl.
42. V.Q. is a Marie Curie research fellow of the European Union (grant HPMF-CT-1999-00052). During the first part of this work, V.Q. was supported by a fellowship of the Spanish SEUID (Ministerio de Educación y Cultura) and partially by Spanish DGES (grant PB96-0797). B.M. is a Royal Society research fellow. Numerical simulations were carried out as part of the Virgo Consortium and the UK Computational Cosmology Consortium.

Photon-Mediated Hybridization of Frenkel Excitons in Organic Semiconductor Microcavities

David G. Lidzey,[1]* Donal D. C. Bradley,[1] Adam Armitage,†
Steve Walker,[2] Maurice S. Skolnick[1]

Coherent excitations of intricate assemblies of molecules play an important role in natural photosynthesis. Microcavities are wavelength-dimension artificial structures in which excitations can be made to couple through their mutual interactions with confined photon modes. Results for microcavities containing two spatially separated cyanine dyes are presented here, where simultaneous strong coupling of the excitations of the individual dyes to a single cavity mode leads to new eigenmodes, described as admixtures of all three states. These "hybrid" exciton-photon structures are of potential interest as model systems in which to study energy capture, storage, and transfer among coherently coupled molecular excitations.

The light-harvesting complexes of photosynthetic bacteria act to capture, store, and subsequently funnel energy to the reaction center, where electron transfer then initiates the energy conversion that drives life (1). Such processes are extremely fast and efficient and are believed to involve coherent excitations of intricate assemblies of macrocyclic chromophores. However, the details of their operation are still not fully understood (2). Nature has designed systems in which the three-dimensional structure appears to play a key role in optimizing the individual steps. Optical microcavities, by contrast, are wave-length-dimensional artificial structures, often less sophisticated in construction, in which excitations can be made to couple through their mutual interaction with confined photon modes. We present microcavity structures in which two remotely separated organic dyes are simultaneously strongly coupled to the same standing-wave optical mode. One may describe this coupled system in terms of a photon-mediated hybridization between the two exciton states. Such devices are of interest in studying coherent Frenkel-exciton coupling. They also bear analogy to the coupled chromophore systems found in nature.

A planar microcavity is a structure that consists of wavelength-thickness semiconductor layers positioned between two mirrors. The cavity quantizes the local electromagnetic field into a discrete set of confined photon modes. If the energy of one of these modes is resonant with an optical transition of the semiconductor, it is possible to modify

¹Department of Physics and Astronomy, Hicks Building, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, UK. ²Department of Electronic and Electrical Engineering, Mappin Street, Sheffield S1 3JD, UK.

*To whom correspondence should be addressed. E-mail: d.g.lidzey@sheffield.ac.uk
†Present address: Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK.