SECULAR EVOLUTION VERSUS HIERARCHICAL MERGING: GALAXY EVOLUTION ALONG THE HUBBLE SEQUENCE, IN THE FIELD AND RICH ENVIRONMENTS

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Abstract
In the current galaxy formation scenarios, two physical phenomena are invoked to build disk galaxies: hierarchical mergers and more quiescent external gas accretion, coming from intergalactic filaments. Although both are thought to play a role, their relative importance is not known precisely. Here we consider the constraints on these scenarios brought by the observation-deduced star formation history on the one hand, and observed dynamics of galaxies on the other hand: the high frequency of bars and spirals, the high frequency of perturbations such as lopsidedness, warps, or polar rings. All these observations are not easily reproduced in simulations without important gas accretion. N-body simulations taking into account the mass exchange between stars and gas through star formation and feedback, can reproduce the data, only if galaxies double their mass in about 10 Gyr through gas accretion. Warped and polar ring systems are good tracers of this accretion, which occurs from cold gas which has not been virialised in the system’s potential. The relative importance of these phenomena are compared between the field and rich clusters. The respective role of mergers and gas accretion vary considerably with environment.

Keywords: Galaxy – Evolution – Hubble sequence – accretion – star formation – Interactions – mergers

1. Introduction

Galaxies grow from small mass systems, the first structures to be unstable after recombination are of the order of a globular cluster mass (~ 10^6 M☉). Then, according to the hierarchical scenario of galaxy formation, small systems merge to form larger and larger systems, and in the same time, small structures accrete gas mass and dark matter from larger gaseous structures in the shape of filaments in the cosmic web.

The relative importance of these two essential ways to build galaxies, through mergers or external gas accretion, is still unprecised in the numerical simula-
tions, since it depends on many unknown parameters of the baryonic physics, gas dissipation, star formation efficiency, feedback, gas re-heating, etc. However, the dynamical history of galaxies strongly depends on these processes, and it might be possible to find constraints on them from the observations, locally and at various redshifts, of the dynamical states of galaxies.

Interaction with massive companions and mergers tend to heat the stellar component of galaxies, and to form the spheroids, either increase the mass of the central bulge, or even transform the system in a giant ellipticals in case of major mergers. On the contrary, gas accretion can replenish the young disk in spiral galaxies, and rejuvenate spiral or bar waves, and reduce the bulge-to-disk ratio. The thickness of galaxy disks, and their ability to maintain spiral structure and asymmetries is a tracer of their history, in terms of interactions or gas accretion. I will review here the recent progress in obtaining these constraints, both on the observational side, which provides statistics of the dynamical state of spiral galaxies, and on the theoretical side, which provides the interpretation through predictions of this dynamical state under several hypothesis about the past history of galaxies.

Section 2 reviews the star formation history of galaxies in the field, and Section 3 the constraints from the dynamics: bars, warps, polar rings and asymmetries. Section 4 considers the same phenomena in clusters, and conclusions about secular evolution as a function of environment are drawn in Section 5.

2. Star formation history

Models of the chemical evolution of the Milky Way suggest that the observed abundances of metals require a continuous infall of gas with metallicity about 0.1 times the solar value. This can solve the well-known G-dwarf problem, i.e. the observational fact that the metallicities of most long-lived stars near the Sun lie in a relatively narrow range (-0.6 \( < [\text{Fe/H}] < +0.2 \), Rocha-Pinto & Maciel 1996). The infall of gas is also supported by the constant or increasing star formation rate (SFR) scenario inferred from the local distribution of stars (e.g. Haywood et al. 1997). Other abundance problems require also an infall rate integrated over the entire disk of the Milky Way of a few solar mass per year at least (Casuso & Beckman 2001). This infall dilutes the enrichment arising from the production of heavy elements in stars, and thereby prevents the metallicity of the interstellar medium from increasing steadily with time. Some of this gas could come from the High Velocity Clouds (HVC) infalling onto our galaxy disk (Wakker et al. 1999).

The High-Velocity Clouds (HVCs) observed in the Galactic neighbourhood, at least those not included into the Magellanic Stream more akin to tidal debris, have been proposed to be remnants of the formation of the galaxies in the Local Group (Blitz et al. 1999). With distances much larger than previously
assumed (i.e. 1 Mpc instead of 100 kpc), their gas masses could represent a large fraction of the total baryonic mass of the Local Group. This hypothesis is supported by observational evidence that their kinematical centre is the Local Group barycentre (Blitz et al 1999). Within this hypothesis, HVCs can well explain the evolution of the light elements in the Galaxy, and the G-dwarf problem (Lopez-Corredoira et al 1999). The present infall rate of gas is estimated to be 7.5 Mo/yr (Blitz et al 1999). This is the right order of magnitude to double the baryonic mass of the Galaxy in 10 Gyr time-scale. The HVCs, whose properties are very similar to the higher redshift Lyα forest clouds, may thus form a significant constituent of baryonic, and of non-baryonic, dark matter.

It is now possible to investigate the star formation evolution in nearby galaxies as well: Worthey & Espana (2004) with HST colour-magnitude diagrams derived a stellar abundance distribution for M31. The results are quite similar to what is observed in the solar neighbourhood and they concluded that closed-box models in M31 suffer a G-dwarf problem even more severe than in the Milky Way.

The star formation rate in the Milky Way disk has remained of the same order of magnitude over the galaxy life-time (Rana & Wilkinson 1986), although some temporal fluctuations can be identified (Rocha-Pinto et al 2000). This appears to be a general results for spiral galaxies in the middle of the Hubble sequence (e.g. Kennicutt 1983, Kennicutt et al 1994).

Figure 1. Star formation rate history of two galactic-like objects modelled by Tissera (2000). The arrival of a companion is indicated an arrow pointing up, and the merging of the baryonic cores by an arrow pointing down.

To maintain the same order of magnitude for star formation rate requires external gas accretion, since an isolated galaxy must have an exponentially decreasing star formation rate, even taking into account stellar mass loss. Numerical simulations of galaxy evolution, in a general cosmological frame, have
shown that indeed a typical spiral galaxy in average environment, maintains a constant level of star formation rate, with superposed bursts (Tissera 2000, Nagamine et al 2004). While simulations of isolated galaxy mergers reveal how star formation is triggered by interaction and mergers (e.g. Mihos & Hernquist 1996), they cannot maintain a constant average level of star formation, as in cosmological simulations.

Figures 1 and 2 shows several histories of star formation for galaxy-like objects at $z = 0$, from Tissera (2000) and at $z = 3$, Nagamine et al. (2004). The history has been obtained by reconstructing the merging tree, in identifying the progenitors of the present galaxy with the particles it is made of in the simulation, a companion being defined by having at least 10% of the main galaxy mass (the accretion of baryonic clumps are assimilated to external gas accretion). Each time such a companion enters the main halo, an up arrow is drawn, and each merger is traced by a down arrow. Several phenomena can be emphasized: a large fraction of gas is accreted between mergers, and this contribute an essential part of the star formation. The tidal interaction triggers bursts of star formation, which in general are delayed with respect to the first passage, but the bursts are not only fuelled by the accreted companion gas, but mainly from the main galaxy gas driven in by the tidal forces. In that sense, the external gas accretion in between mergers also fuels the merger-triggered starbursts.

Observations of stellar populations in a large sample of local galaxies (SDSS, Heavens et al 2004, Jimenez et al 2004) have shown that massive galaxies have formed most of their stars at early times, while dwarf galaxies are forming their stars efficiently only now. Only intermediate mass galaxies could have
in average maintained their star formation rate over a Hubble time. The high efficiency of star formation in massive galaxies underlines the role of environment, and the availability of high gas accretion. The rate of gas consumption is then high, and the galaxies run out of gas quickly. On the contrary, far from deep potential wells, dwarf galaxies need billion years to reach the threshold of star formation, and convert their gas only now.

In semi-analytic models, an essential free parameter to reconstruct merger trees and mass assembly in galaxies, in the fraction of accretion, and this can change considerably the final angular momentum of the system (Wechsler et al 2002). Figure 3 illustrates the time evolution of the baryonic content of halos that correspond to a "local group" \( (V = 220 \text{ km/s}) \) sized halo at \( z = 0 \). This evolution corresponds to the best fit of the observations, i.e. the luminosity function of galaxies and the Tully-Fisher relation. The star formation rate has been calibrated, so that the star formation efficiency is constant with redshift (Somerville & Primack 1999). Note that the fraction of available gas in the form of cold phase remains quite high until \( z = 0 \).

![Figure 3](image)

**Figure 3.** The fraction of cold and hot gas, and the history of star formation in halos of size \( V_c = 220 \text{ km/s} \) at \( z = 0 \), in a standard CDM model, computed with semi-analytic models by Somerville & Primack (1999).

As far as the global gas content is concerned, constraints can be found in the frequency and column densities of the damped Lyman-\( \alpha \) systems (DLA). Already at high redshift, the models are limited by the observations, which then constrain the star formation rate (fig 4). A strong starburst mode is required in
addition to quiescent star formation mode, as triggered by the frequent mergers around $z \sim 2 - 1$. Note that the observational points only correspond to HI gas of column density larger than $2 \times 10^{20} \, \text{cm}^{-2}$, ignoring molecular or ionised gas, that could bring the model closer to observations at low redshift.

Figure 4. Cold gas density versus redshift, computed in semi-analytic models by Somerville & Primack (1998). The bold solid line includes starbursts, while the light line only quiescent star formation. Data points show the density in the form of HI estimated from observations of DLA (Storrie-Lombardi et al. 1996). The point at $z = 0$ is from local HI observations (Zwaan et al 1997).

3. Constraints from the dynamics

Several dynamical processes can be naturally explained with external gas accretion, and could be used as constraints on the amount of gas available, they are summarised in fig 5.
Bars and secular evolution

From observations and numerical simulations in the last decades, secular evolution has been shown to be driven by bars and spirals (e.g. Kormendy & Kennicutt 2004). In particular, the bar gravity torques produce radial gas inflow, generating star formation. Dynamical instabilities then regulate themselves, since the gas inflow itself can destroy the bar. The bar is destroyed by two main mechanisms: first the central mass concentration built after the gas inflow, destroys the orbital structure sustaining the bar, scatter particles and push them on chaotic orbits (Hasan et al 1990, 1993, Hozumi & Hernquist 1999). Second, the gas inflow itself weakens the bar, since the gas loses its angular momentum to the stars forming the bar (Bournaud & Combes 2004). This increases the angular momentum of the bar wave, in decreasing the eccentricity of the orbits. This bar destruction is reversible, since the central mass concentration is then not strong enough to prevent bar formation.

Secular evolution then includes several bar episodes in a galaxy life-time. A spiral galaxy rich in gas (at least 5% of the disk mass) is unstable with respect to bar formation. Gravity torques are then efficient to drive the matter inwards. The galaxy morphological type evolves towards early-types, the mass is concentrated, the bulge is developed, through horizontal and vertical resonances. This weakens the bar, and when the galaxy becomes again axi-symmetric, gas can be accreted from the outer parts by viscosity (Bournaud & Combes 2002). The gas accretion, if significant with respect to the disk mass, can reduce the bulge-to-disk ratio (by replenishing the disk), and make the galaxy disk unstable again to a new bar.

Several bars can successively produce secular evolution of spiral galaxies, if there is enough external gas accretion. This can be used to quantify the amount of accretion in a galaxy life-time.

To estimate the number of bars that has occurred in a typical galaxy, and the time spent in a bar phase, Block et al (2002) have estimated quantitatively the frequency of bars and $m = 2$ spiral components in a sample of 163 spiral galaxies, observed in the near-infrared (Eskridge et al 2002). In this band, it is more easy to identify the bars in the old stellar component, with limited dust extinction.

The bar strength $Q_b$ has been estimated from the gravitational potential, derived from the NIR images, assuming constant mass-to-light ratios. The main surprising result in the histogram of bar strength is the hole at low values (lack of axi-symmetric galaxies), and a long tail at high values, corresponding to a large number of strongly barred galaxies (see also Whyte et al 2002, Buta et al 2004).

It can be concluded from the comparison of bar life-times given by numerical simulations, and the observation of bar frequency, that bars have to be
reformed, and this can only be through significant accretion of external gas (see Bournaud & Combes, this volume).

**Warps**

Most spiral galaxies reveal a warped disk, particularly spectacular in the HI component (Briggs 1990), although it is still frequent in the optical disk (Reshetnikov & Combes 1998). Many physical mechanisms have been studied to explain the origin of these warps (see the review by Binney 1992), but the high frequency of warps is only accounted for by external gas and dark matter accretion. Matter accreted in the outer parts of a dark matter halo, with an angular momentum misaligned with that of the inner parts, can re-oriented the whole system in 7-10 Gyr, and the corresponding disk will show an integral-sing warp during the process (Jiang & Binney 1999). Intergalactic gas accretion is sufficient to produce a torque corresponding to the observed warps, with the infall amplitude already required by evolutionary chemical models (Lopez-Corredoira et al 2002). During some transient phase, a U-shape warp is predicted, combining m=0 and m=1 perturbations, and its frequency corresponds to the observations. The galaxy has just to move in an accretion flow of average density of $10^{-4} \text{ cm}^{-3}$, and velocity 100 km/s.

Bullock et al (2001) have explored the angular momentum distribution in a large number of dark matter haloes, from a cosmological simulation. They found an almost universal form, with a moderate misalignment in the outer parts, that could also favor warps in the baryonic matter. However, both the halo growth through merger of smaller units, and quiescent and continuous accretion are able to produce the same universal profile, so this will not be discriminant.

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*Figure 5.* Dynamical processes constraining the external gas accretion, illustrated by prototypical examples, from left to right: frequency of bars in galaxies (NGC 1365), frequency of warps (NGC 4013), polar rings (NGC 4650A), and lopsidedness (M101).
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Polar rings

Polar ring galaxies are particular objects, composed of a primary galaxy in general of early-type (lenticular or elliptical), and a polar ring or disk, where the matter is orbiting in a nearly perpendicular plane. The polar material is quite gas-rich, but also composed of stars, of age larger than a few Gyrs, implying that the polar disk is stable. Indeed, in any of the various scenarios advanced to account for this structure, the bulk of the stars form later from the gas settled in the polar plane. The probability for a galaxy to have a polar ring has been estimated to $\sim 5\%$, given the detection biases, that these systems are better detected edge-on (Whitmore et al 1990).

The two main scenarios to form polar rings are mergers of two galaxies, or external gas accretion, this gas coming either from a passing-by companion, or from a cosmic gaseous filament. In the merging scenario (Bekki 1997, 1998), a special geometry is required for the two interacting system, it must be a head-on collision at low velocity, with the two galaxy planes nearly perpendicular to each other. In the accretion scenario, gas may be accreted from an unbound companion passing by (Schweizer et al. 1983, Reshetnikov & Sotnikova 1997), in a nearly polar orbit. The companion must be gas-rich, and may also be more massive than the primary. But gas could also come from a gaseous cosmic filament, during the long formation period of a giant galaxy, since the various filaments have not the same orientation. This is the extreme case of the warp formation mechanism, invoked in the last subsection, where the various accreted gas have not aligned angular momentum. Intermediate cases between warps and polar rings, where rings of gas orbit at around 45°, are observed (for instance NGC 660). Polar rings around galactic-like objects are frequently seen in cosmological simulations (Semelin & Combes 2004).

From a large number of numerical simulations, exploring the various geometrical or mass parameters of the two scenarios, it has been shown that the accretion scenario is more likely to produce polar rings, corresponding to observations, than the merger scenario (Bournaud & Combes 2003). In addition to this statistical argument, some prototypical cases, like NGC 4650A, support the accretion hypothesis, since they do not possess a halo of very old stars, expected in the merger scenario.

Lopsidedness

The observation of extended disks of neutral hydrogen (through the HI line at 21cm) around most spiral disks, has revealed a large frequency of asymmetries and lopsidedness. In their compiled sample of 1700 galaxies, Richter & Sancisi (1994) found that at least 50% of spiral galaxies are lopsided, and have a characteristic signature in their global HI spectrum. This percentage is even higher in late-type galaxies, where Matthews et al (1998) found a frequency of
77% of HI distorted profiles. The asymmetries affect also the stellar disk, as shown by Rix & Zaritsky (1995) and Zaritsky & Rix (1997) on near-infrared images of galaxies. About 20-30% of galaxies have a significantly perturbed stellar disk, quantified by the $m = 1$ Fourier term in their potential or density distribution (Kornreich et al 1998, Combes et al 2004).

Since most of these galaxies are isolated without obvious sources of perturbations (e.g. Wilcots & Prescott 2004), the interpretation was searched in a possible long life-time of these features. Baldwin et al. (1980) proposed that the lopsidedness comes from $m = 1$ kinematic waves build from off-center elliptical orbits that may persist a long time against differential precession. Although this can prolonge the life-time significantly, since the winding out by differential precession is quite long in the outer parts of galaxies, they conclude that it is still not sufficient to explain the high frequency of lopsidedness in neutral gas disks.

Alternatively, the perturbations could come from recent minor mergers, explaining the non-correlation with the presence of companions (Zaritsky & Rix 1997). In this hypothesis, lopsidedness can be used to constrain the merger frequency, which appears very high. Indeed, Walker et al (1996) have estimated through N-body simulations that the life-time of perturbations are of the order of the Gyr. A high merging frequency may enter in conflict with other observations, for instance the presence of thin stellar disks in spiral galaxies (Toth & Ostriker 1992).

External gas accretion could solve the problem of the high frequency of lopsidedness, since it is likely that in many cases, the accretion is asymmetric.

4. Environmental effects

The relative role of galaxy merging and external gas accretion must depend strongly on environment. In particular, in rich clusters, mergers have considerably increased the fraction of spheroids and ellipticals, and tidal interactions and ram pressure have stripped and heated the cold gas around galaxies, so that external accretion will be reduced or suppressed. To quantify theses effects, we consider successively the influence of environment on star formation rate, morphological types, and dynamical features, such as bars or warps.

Star formation history

High resolution images with the HST, followed by spectroscopic surveys in a dozen galaxy clusters at redshift around 0.3-1. have allowed to follow galaxy evolution and in particular their star formation history as a function of time, and also position in the cluster (Oemler et al 1997, Dressler et al. 1999, Poggianti et al 1999).
Rich clusters of galaxies, and especially their dense cores, are well known to be dominated by early-type galaxies without star formation, or even passively evolving and anemic spirals, conspicuous for their low star-formation rate. To find star formation it is necessary to look back in time, at redshift at least larger than 0.2, where there exists a larger fraction of blue galaxies (B-O effect, Butcher & Oemler 1978, 1984). The recent HST images have shown that these blue galaxies are disk galaxies in majority perturbed by tidal interactions, strongly suggesting that galaxy interactions are still triggering star formation activity around $z = 0.5$ (Lavery & Henry 1988).

There is thus a strong evolution effect in clusters in a recent past. Moreover, detailed spectroscopic studies have shown that $z \sim 0.5$ clusters possess a large fraction of peculiar galaxies, likely post-starburst, called E+A (or k+a), devoid of emission lines (and therefore with no current star formation), but very strong Balmer absorption lines. (Dressler et al 1999, Poggianti et al 1999). This means that they have a large fraction of A stars, implying that the galaxy was experiencing a strong starburst that has just been abruptly interrupted. These galaxies are in majority disk-dominated. Their fraction is about 20%, much larger than in the field, and in the clusters at $z = 0$ (Dressler et al 1999).

That star formation is quenched in clusters is revealed by the low fraction ($\sim 10\%$) of H$\alpha$ emitters; star formation and morphological evolution in cluster galaxies appear to be largely decoupled (Couch et al 2001). On the contrary, the star formation is continuing in groups. About 55% of galaxies have been cataloged in groups at $z < 0.1$ in the 2dF and SDSS surveys, and the H$\alpha$ detection rate and equivalent width varies strongly and continuously with galaxy density (Balogh et al 2004).

The star formation rate, as traced by the H$\alpha$ line, is strongly dependent on the density of galaxies (Lewis et al 2002, 2dF survey). There is a tight correlation between SFR and local projected density, as soon as the density is above $\Sigma = 1$ galaxy/Mpc$^2$, independent of the size of the structure. In clusters, the field star formation rate is only recovered at about 3 times the virial radius. Gomez et al (2003) find also a strong SFR-$\Sigma$ relation with the early data release of the SDSS, the SF-quenching effect being even more noticeable for strongly star-forming galaxies. The same break of the SFR-$\Sigma$ relation is observed at 1 galaxy/Mpc$^2$. This relation is somewhat linked to the morphological type-density (T-$\Sigma$) relation, but cannot be reduced to it.

The spatial distribution of star forming galaxies is also quite clear in clusters. There is a clear radial gradient, the star formation being more active in the outer parts (Balogh et al 1999). There is a smooth transition from a blue, disk-dominated galaxy population in the outskirts, to a red, bulge-dominated, galaxy population in the cluster cores. Although this is influenced by the various transformation processes occuring in clusters (tidal interaction, mergers, harrassment, ram-pressure...), this has been mainly interpreted in terms of the

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building up of the clusters themselves, i.e. gas-rich galaxies continue to fall into the cluster, and contribute to the star-formation activity there, but then their gas replenishment is stopped when these galaxies arrive into the core (Diaferio et al. 2001). In a model where the morphology of galaxies are assumed to depend only on their merger history, where mergers lead to spheroid and bulges, and subsequent gas cooling replenishes disks, it is possible to reproduce the morphological gradient, and star-formation gradient observed. Galaxies in clusters are much sooner devoid of their gas, and their gas fueling is stopped, as shown in Figure 6.

Figure 6. The ratio of gas mass to stellar mass as a function of redshift for galaxies larger than $3 \times 10^{10} \, M_\odot$ in clusters (top) and in the field (bottom), from semi-analytical models by Diaferio et al (2001). The dashed lines correspond to SFR proportional to the cold gas mass over the dynamical time. The solid lines include in addition a dependency of the SFR with redshift as $(1+z)^{-1.5}$.

**Morphological types**

There is a strong morphological segregation as a function of projected density $\Sigma$ at $z = 0$ (Dressler 1980), essentially the fraction of spirals fall from two
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thirds to less than one third to the benefit of lenticulars and ellipticals. This segregation has also been observed at \( z = 0.4 \) (or 5Gyrs ago), where the fraction of ellipticals is the same as at \( z = 0 \) (Dressler at al 1997). The difference is in the fraction of lenticulars, which is less than at \( z = 0 \). This suggests that the formation of elliptical galaxies occurs before the formation of rich clusters, probably in the loose-group phase or earlier. Lenticulars are generated in large numbers only after cluster virialization, through the various galaxy transformation processes, tidal interactions, mergers, ram-pressure stripping and sudden halt in gas fueling (Poggianti et al 2001). These results have been confirmed and precised with the local Sloan survey by Goto et al (2003); at least two mechanisms are required to explain the morphological segregation: first at low density in the outskirts of the cluster, the gas supply is stopped, and star formation halted. Second at high density, in the cluster core, galaxy interactions and merging must explain the high frequency of early-types. The segregation is also found quite similar at \( z = 0.5 \) and locally, confirming that ellipticals in clusters have formed earlier. This corresponds to numerical simulations, which show that the halos located inside clusters form earlier than isolated halos of the same mass (Gottloeber et al 2001).

Many aspects of galaxy morphology in clusters can be explained by evolutionary processes (see the reviews by Moore 2003, Combes 2003), but the fact that the gas supply is halted plays in all these processes a major role (Shioya et al 2004 and fig 7): this gas shortening could happen in two ways, either gradual from gas stripping, and star formation rate dropping subsequently, or abruptly, through a starburst triggered by an interaction, and lack of gas supply afterwards. The second way is necessary to explain the high frequency of post-starburst systems (k+a) in distant clusters, and the low frequency of strong H\( \alpha \) line emitters.

**Frequency of bars, warps**

Spiral galaxies are globally less abundant in clusters, and are preferentially located in the outskirts. It has long been known that clusters are the site of a particular class of spirals, called "anemic", with low star formation, smooth arms, and low gas content (van den Bergh 1976). In average, anemic galaxies have an HI deficiency of a factor 4, but no CO emission deficiency, their spiral structure is fuzzy and short-lived, since new stars with low velocity dispersion are no longer formed out of the gas (Elmegreen et al 2002).

The frequency of bars in cluster spirals has been studied in order to test the influence of tidal interactions by Andersen (1996) for the Virgo cluster. Barred galaxies appear to be more centrally concentrated in the cluster core than unbarred galaxies. This is inferred from both velocity dispersions which are quite different. On the contrary, barred or unbarred lenticulars have the
Figure 7. Evolution with time of the halo gas mass (normalized to the initial mass), for a spiral galaxy orbiting a cluster with a pericenter distance $R_p$ equal to 3.2 the scale radius of the cluster $R_s = 230$ kpc (solid line). By comparison, the dashed line corresponds to a comparable orbit in a group with $R_s = 62$ kpc, and the dotted line, with $R_p = 0.3 R_s$ in this group (from Bekki et al 2002).

same radial distribution in the cluster. Andersen (1996) suggests that tidal triggering by the cluster itself is the most likely source of the enhanced fraction of barred spirals in the cluster center. The same phenomenon is observed in Coma (Thompson 1981). Bars occur twice as often in the core region of Coma as they do in the outer parts of the cluster. This is certainly the consequence of tidal interactions triggering bar instability (Gerin et al. 1990, Miwa & Noguchi 1998, Berentzen et al 2004).

At a global scale however, there does not appear to be any significant difference between the frequency of bars in clusters and in the field (van den Bergh, 2002). Because bars are triggered by galaxy interactions in the cluster cores, this implies that the suppression of gas supply in clusters has a tendency to reduce bar frequency to compensate.

It is difficult to observe warps around spiral galaxies in clusters, because of their characteristic general HI deficiency. About two thirds of galaxy clusters are HI deficient (Solanes et al. 2001). Gas is particularly stripped in the outer parts of galaxies, where warps develop.
Polar rings and asymmetries

The environment of polar ring galaxies seems to be similar to that of normal galaxies (Brocca et al 1997). There is no evidence of more companions for example. Some polar ring galaxies are observed in clusters (Taniguchi et al. 1986). As for asymmetries, they are very frequent in clusters, but this has to be attributed to galaxy interactions; in a Hubble time, each galaxy suffers about 10 encounters with an impact parameter less than 10kpc, due to the importance of substructures (Gnedin 2003).

Figure 8. Distribution of the hot gas fraction $f_g$ in clusters of galaxies as a function of $\delta$, the average density inside the radius $r$ (normalised to the critical density). The filled circles, empty triangle and crosses are the data, while the squares connected by a dashed line are the theoretical predictions (cosmological simulations from several groups), with an assumed baryon fraction of $f_b = \Omega_b/\Omega_m = 0.16$; other models (with or without stellar feedback) are shown with $f_b = \Omega_b/\Omega_m = 0.20$ (small squares), from Sadat & Blanchard (2001)
5. Summary

The mass assembly of galaxies occurs through two main processes: hierarchical merging of smaller entities, and more diffuse gas accretion. The relative importance of the two processes cannot be easily found by cosmological simulations, since many physical parameters such as gas dissipation, star formation and feedback, are still unknown. However, star forming histories in galaxies (age, kinematics and metallicity), and also the dynamical states of galaxies (bars, spirals, warps, polar rings, asymmetries..) can constrain the role of the two processes.

Chemical evolution of normal spiral galaxies requires gas infall of low-metallicity gas, in the proportion of a few solar masses per year. The development of bars and spirals in galaxies constrain the amount of external gas accretion at about $10 \, M_\odot/\text{yr}$. Bars are transient features in galaxies, they exert gravity torques on the gas component, and drive mass to the center. A new bar can reform in disks that have been replenished in gas. The large frequency of gaseous warps in the outskirts of galaxies require also continuous gas accretion, with misaligned angular momentum. When the accreted gas has perpendicular angular momentum, a polar ring can be formed. Asymmetric gas accretion could be responsible for frequent lopsided galaxies.

In rich environments, the evolution is occurring at a much quicker pace. Galaxy interactions and mergers are much more frequent, and happen earlier in the Hubble time. The star formation activity triggered by the mergers must have occurred early in dense groups that coalesce then in galaxy clusters. Most of the star formation is then quenched after redshift $z \sim 1$. The only activity remaining comes from the infall of field spiral galaxies in the outer parts of the clusters. Secular evolution through external gas accretion is slowed down or halted, since galaxies are stripped from their gas, at large galactocentric radii. Most of the gas has been shock-heated at the virial temperature of the clusters, and is observed in X-rays. The mass fraction in hot gas reaches the baryonic fraction in the outer parts (e.g. Sadat & Blanchard 2001, fig 8, Valageas et al. 2002). Contrary to the field, it appears that hierarchical merging has dominated secular evolution in rich galaxy clusters.

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