Secular Evolution of Galaxies

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In current ΛCDM galaxy formation scenarios, at least three physical phenomena could contribute to the mass assembly: monolithic collapse, hierarchical mergers and more quiescent external gas accretion, with secular evolution. The three processes are described, and their successes and problems are reviewed. It is shown that monolithic collapse is likely to be quite restricted to sub-components of galaxies, while the two main scenarios, hierarchical merging and secular evolution, might have comparable roles, depending on environment. Evidences are reviewed for the important role of gas accretion, followed by secular evolution. In particular the existence of thin and cold disks, the occurrence of bars and spiral structure, the frequency of lopsided instabilities, and the history of star formation, all point towards large amounts of cold gas accretion. Some examples of N-body simulations are reviewed in support of secular evolution.

1 The three main processes/scenarios of galaxy formation

1.1 Monolithic Collapse (MC)

The scenario of monolithic collapse for the formation of the Galaxy was suggested by Eggen, Lynden-Bell and Sandage (1962, ELS), on the basis of the observed correlation between [Fe/H] and orbital eccentricity $e$ for old stars. Since stars with low metallicity had very low angular momentum $L_z$, they suggested that the old stars were formed out of gas falling towards the center in radial orbits, collapsing quickly from a halo to a thin rotating disk plane enriched in heavy elements by star formation. In this picture, the gravitational potential is varying slowly and the stellar parameters $e$ and $L_z$ can be considered as invariants.

In an opposite view, Searle & Zinn (1978) consider that the ELS results are simply the consequence of the selection bias on high proper motion stars. They remark that halo globular clusters have a large range of metallicity, with [Fe/H] uncorrelated with distance, and favor a formation through merging of small protogalaxies. The gravitational potential is varying rapidly in this view, and there is also substantial gas accreted later.
The monolithic collapse scenario for our Galaxy is not viable anymore, or only for a restricted component, the central bulge. The stellar halo is smaller than the disk, and could not collapse into the disk. The only galactic component to collapse into is the old bulge (Gilmore 1996). Note however that, although the bulge stars are old, they have high metallicity, as the disk, so this is not easily explained by this scenario.

Rapid monolithic collapse is not likely to be the main formation process of most normal galaxies, since huge ULIRGs at high redshift are very rare. In any case, departures from MC are larger in low-mass galaxies (Ferreras & Silk 2000).

1.2 Hierarchical scenario (HS)

In this frame, a system like our own Galaxy is the result of the hierarchical assembly of dark halo building blocks. Accretion of baryonic gas occurs later, in the assembled structure, to form the bulge, and progressively the thin disk, which forms last. The thick disk could be due to the past heating of the thin disk by companions.

This scenario is supported by the existence of stellar streams in the stellar halo (Helmi 2002, Ibata et al 2002): they are tidal debris from the accretion of small companions. The halo could be entirely built from these minor mergers.

The observed large increase with redshift of the merger frequency comes in support of the hierarchical scenario. This is particularly spectacular in galaxy clusters, for massive galaxy formation (e.g. van Dokkum et al 1999). In some massive ellipticals, two populations of globular clusters have been detected, hinting towards two major merging episodes, triggering their formation (Zepf & Ashman 1993).

1.3 Secular Evolution, with slow and continuous external matter accretion (SE)

In secular evolution, the bulge component is formed slowly from the disk through the bar action, and the disk can be replenished through continuous external gas accretion. The Galaxy can be considered an open system, with slow mass growth through time, from external accretion of gas progressively transformed into stars, and the various components interacting with each other.

According to a statistical analysis of 257 spiral galaxies, the radial color gradients observed and the relation between disk and bulge colors favor the formation of bulges through SE (Gadotti and dos Anjos 2001). SE is also supported by the relation between bulge and disk masses and radii (Courteau et al 1996).

In a large sample of early-type galaxies, moderate radial gradients of metallicity are observed, which are independent of luminosity (De Propris et al 2005). Ellipticals and bulges of lenticular galaxies reveal similar behaviour. These observations are contrary to what is expected with MC (large gradients which should increase with mass and luminosity) and contrary to what is predicted by HS (which smears out gradients).

Cosmological simulations based on a ΛCDM universe may include all processes with different emphasis, according to the treatment of baryon physics. In addition to hierarchical merging of dark haloes, the hot gas is cooling in dark haloes within the cooling radius, and contracts monolithically to form galaxies. However, the gas infall might also occur in fragmented and dense colder gas clouds (Maller & Bullock 2004), or the gas accretion could be continuous, and favor secular evolution.

Successive episodes of dissipational collapse, followed by mergers, lead in numerical simulations to elliptical-like objects, which are in better agreement with observations than the results of stellar disks mergers only (Meza et al 2003). In this scenario, the final merger episode forms hot gas, the absence of cooling prevents star formation, and the final object is an elliptical, with no recent accretion, and consequently an old stellar population with no disk morphology.
2 Successes and difficulties of the different processes

2.1 Massive galaxies early in the universe

Very massive elliptical systems ($10^{11} M_{\odot}$), possessing a large fraction of old stars, have been observed in deep optical and near-infrared surveys, at redshifts between 1 and 2 (Daddi et al 2004, Cimatti et al 2004). The presence of these rather evolved systems, when the universe was only 25% of its age was a surprise, since it is expected that massive ellipticals are the end result of the hierarchical merging process.

However, these massive objects are highly clustered and appear to correspond to the early formation of groups in rich environments. It is predicted that evolution proceeds much more rapidly in those environments with respect to the field, and the presence of some fraction of massive objects is thus expected.

Such massive objects can be traced by their star formation, either by optical techniques, when their light is not highly obscured, or in Lyman Break Galaxies (LBG), or through their dust emission in the far-infrared, redshifted in the submillimeter range. The latter are then called SMGs (SubMillimeter Galaxies), and are found preferentially between $z=1$ and 4. The physical nature of these objects can be determined more precisely when CO emission is detected. Given their gas content, and star formation rate (larger than 700 $M_{\odot}$/yr), their life-time is between 40 Myr and 200 Myr (Greve et al 2005). The correlation between the Far-Infrared and CO emission suggests that they are the equivalent of local ULIRGs, with an even more efficient star formation rate. These starbursts are associated to galaxy mergers, which could be more violent than locally, since bulges are less prominent at high redshifts.

The number of SMGs detected can be used to estimate the density of massive galaxies at these redshifts (Greve et al 2005). The estimate is a lower limit, since the life-time of the starburst phase is not precisely known (and the correction is made with the conservative value of 200 Myr). Within the error bars, the derived number density of SMGs is compatible with the predictions of the $\Lambda$CDM simulations and semi-analytical calculations, if 10% of baryons are rapidly converted into galaxies (cf Figure 1).

This agreement with observations is obtained in the new model from Baugh et al (2005) through a few changes in the assumptions of the semi-analytical simulations, in particular a much larger influence of bursts in the star formation history, a longer time-scale for star formation in disks, and most important, the assumption of a top-heavy IMF in starbursts at high redshift. The consequences of the new model are that the star formation is dominated by bursts at redshifts larger than 4, and later by quiescent mode (while it was dominated by the quiescent mode at all redshifts before). Integrated over the Hubble time, bursts are now responsible for 30% of all star formation (Baugh et al 2005). Massive galaxies today have only a few percent of their stars formed in bursts at $z \sim 2$. The galaxy formation is still quite far from the monolithic collapse view, since the bulk of the stars in massive ellipticals is formed in disks, and then rearranged in spheroids during mergers. Note that the estimated baryonic mass of SMGs has now been re-scaled to $0.6 M_\ast$ in average, while it was 4 times larger before (Greve et al 2005).

2.2 Star formation history versus mass

The star formation history (SFH) has been derived from the direct observations of young stars in distant galaxies at different redshifts, which reveal a peak in the star formation rate about 8 Gyr ago, and then a decline by a factor of $\sim 10$. Alternatively, the study of the fossil record of stellar populations, in the local large sample of galaxies in the SDSS has also led to a similar star formation history, with a peak occurring slightly later, about 5 Gyr ago (Heavens et al 2004, Jimenez et al 2004). This study also shows that the SFH is different according to the mass. Stars in massive galaxies appear to have formed at early times, and these galaxies are not actively
forming stars now, while dwarf galaxies appear to experience starbursts. Only intermediate masses have in average maintained their star formation rate over a Hubble time.

It has been known for a long time that galaxies in the middle of the Hubble sequence had about constant SFR across the Hubble time (Kennicutt 1983, Kennicutt et al 1994). Even taking into account the stellar mass loss, an isolated galaxy should have an exponentially decreasing star formation history. To account for observations, a source of gas should be found to replenish the star formation fuel in such galaxies. This cannot come from major mergers, which destroy disks, and lead to early-type or elliptical galaxies. On the other hand, small companions are not sufficient, for instance systems falling now on the Milky Way (Sag dw, Canis major, etc..) are of the order of 1/400th of the mass of the Galaxy (Ibata et al 2001, 2003). Accretion of gas from the cosmic filaments should provide the required fuel, which corresponds to a slow and continuous secular evolution.
2.3 Quiescent star formation versus bursts

Below a redshift of $z = 0.7$, which corresponds to about half of the Hubble time, the star formation rate of the universe is dominated by a rather quiescent mode in normal galaxies. But at higher redshift, starbursts begin to dominate, first moderate bursts, giving rise to LIRGs (Luminous Infra-Red Galaxies, with $L > 10^{11} L_\odot$), and after $z=4$, ULIRGs (Ultra-Luminous Infra-Red galaxies, with $L > 10^{12} L_\odot$). Given the shape of the star formation history, most of the stars today have been born in LIRGs (63%), the rest being in ULIRGs (21%) or normal galaxies (16%); this is consistent with the cosmic infrared background (CIRB), which is dominated at least within a proportion of two thirds by LIRGs (Elbaz & Moy, 2004).

The fact that LIRGs are more numerous at $z > 0.4$ (15%) than today ($\sim 1\%$) has been interpreted in terms of recent formation (in the second half of the universe) of the bulk of stars in intermediate-mass galaxies (Hammer et al 2005). At this epoch, LIRGs can account for 38% of all star formation. The high frequency of LIRGs implies episodic star formation bursts, maybe triggered by galaxy interactions. The starburst phase is of the order of 100 Myr, while an interaction is of the order of $10^9$ yrs. This means that all galaxies should be interacting at $z > 0.4$, which is not what is observed.

The frequency of interactions must be lower, but another process could compensate: external gas accretion from the cosmic filaments. Secular evolution could then be responsible for these episodes of star formation. In any scenario, gas must be provided to replenish spiral disks, whatever is the final dynamical trigger, either a passing companion or internal evolution. In both cases, the amount of fuel is the same, the gas from the disk of one (or two) galaxy, and a bar drives the gas towards the center. The gravity torques from the bar can fuel the central disk and star formation intermittently, through self-regulated mechanisms (see below).

2.4 Late bulge formation

Contrary to massive spheroids, consisting of old and red stellar populations, many bulges of spiral galaxies appear to have formed later than their disk. They host young populations, that must have been formed from recent gas inflow followed by star formation, due either to secular evolution or to galaxy interactions. Using the criterion that the color inside the half-mass radius is bluer than the outer parts, Kannappan et al (2004) found that 10% of galaxies in the NFGS (Nearby Field Galaxy Survey) are experiencing bulge growth at the present time.

To distinguish the actual source of gas inflow in those galaxies, a correlation was searched between the blue-center disk characteristic and the presence of companions (see Figure 2). Although there is not a large correlation with the presence of visible companions, there is a strong one with perturbed morphology. The authors then conclude that external drivers, minor mergers or interactions, are more likely the origin of bulge growth today, than internal secular evolution. In fact, as will be developped later, secular evolution can also be driven by external gas accretion, which if asymmetrical, can lead to perturbed morphology as well.

2.5 Respective role of MC, HS and SE

In summary, a certain amount of all three processes are certainly present in galaxy formation, and it is quite difficult to distinguish the relative role of each. For instance, although MC is likely more effective at high redshifts and in high-density environments, it is possible that old stars have been accumulating in massive systems at various redshifts.

Galaxy interactions and mergers increase with $(1+z)^n$, with $m \sim 4$. It has been thus suggested that hierarchical merging dominate in the past and secular evolution will in the future (Kormendy & Kennicutt 2004). But the availability of gas accretion also decreases with time, and it is quite possible that today both processes are occurring with comparable importance,
depending strongly on environment. Both the effects of interactions and gas accretion are quenched in clusters. Even inside a given group, the past evolution appears to depend on morphological type: the Milky Way reveals more signs of secular evolution (pseudo-bulge, old globular clusters...), while Andromeda has experienced a major merger more recently.

The perturbed morphology of galaxies should not always be interpreted in terms of galaxy interactions, it could also be the result of external gas accretion, which is most often asymmetric: lopsided systems, warps, polar accretion... (cf Figure 3). External gas accretion, followed by secular evolution from the bar, can also provide starbursts. The gravity torques of the bar either prevent or favor the gas infall towards the center, as will be described now. The self-regulated bar action results in intermittent periods of activity, starbursts ad well as nuclear activity.

Figure 3: Dynamical processes able to constrain the rate of external gas accretion, illustrated by prototypical examples, from left to right: bars in galaxies (NGC 1365), warps (NGC 4013), polar rings (NGC 4650A), and lopsidedness (M101).
3 Bars and secular evolution

Dynamical instabilities in spiral disks are responsible for its evolution. Detailed numerical simulations since several years have unveiled a self-regulated cycle in this secular evolution. The cycle begins by a first bar instability in a cold spiral disk with stars and gas. When the bar is strong enough, it produces gravity torques on the gas component, due to the phase shift of the gas response (the gas being dissipative). These torques drive gas inflow, from corotation to the center (or ILRs, when they exist). The gas is losing its angular momentum to the benefit of the bar, which is then weakening. The destruction of the bar is due essentially to the gas inflow itself, and also to a lesser degree to the presence of a central mass concentration (CMC), built in the process. Only if enough external gas accretion occurs to replenish the disk mass and trigger another bar instability, can the cycle loop again.

There have been debates about this cycle, in particular about the efficiency of bar destruction, about their ability to reform, and about the required central mass (CMC) to weaken the bar.

3.1 Role of gas in bar destruction

Self-consistent simulations of spiral galaxies with gas have shown that only the infall of 1-2% of mass in gas is sufficient to destroy the stellar bar or to transform it into a lens (Friedli 1994, Berentzen et al 1998, Bournaud & Combes 2002, 2005). But the mechanism of destruction was attributed to the formation of a central mass concentration (CMC), and simulations with the growth of an artificial CMC in the center of a few percent is not enough to destroy the bar (Shen & Sellwood 2004). Now, several simulations with and without gas or CMC have clearly shown the role of gas in bar destruction: gas is driven in by the bar gravity torques, and its angular momentum is taken up by the bar wave. In other words, the reciprocal torques from the gas provides angular momentum to the bar, weakening it, since the bar wave has negative angular momentum inside corotation (Bournaud & Combes 2005). Since the formed CMC is not enough to destroy the bar by itself, it is then more easy to reform a bar, when the disk has become unstable again, through external gas accretion.

In this cycle, it is interesting to note that the galaxy accretes gas towards its center by intermittence. Indeed, while the bar is strong in the disk, the gas from corotation to OLR (Outer Lindblad Resonance) is driven outwards by the positive gravity torques from the bar. Gas is then stalled at the OLR in the border of the disk, prevented to enter. The external gas remains there, while the gas inside corotation is driven inwards, until the bar weakens. After the bar destruction, the external gas can enter and replenish the disk, to make it unstable again to bar formation (see Figure 1). This scenario explains why nuclear activity is not well correlated with the presence of bars in galaxies, even if the gas driven by bars fuels the AGN (e.g. Garcia-Burillo et al 2005). In this frame, AGN activity can be triggered in the weakening phases of the bar.

3.2 Bar frequency

Recent near-infrared surveys have allowed a statistical estimation of bar strength in local galaxies (Block et al 2002, Laurikainen et al 2004). The observed bar frequency is much larger than what is expected for isolated galaxies, where bars should have been destroyed. These statistics can be used to quantify the gas accretion rate, required to reform bars in the right proportions. Note that the bar frequency has been observed comparable at high redshift (Jogee et al 2004), and therefore gas accretion must have played a role all along the Hubble time.

The gas is required to replenish the disk, and maintain it cold and unstable. Not more than 10% of the accretion can be provided by dwarf companions, since interactions between galaxies
heat the disk (Toth & Ostriker 1992), and massive interactions develop the spheroids. The fitting of bar frequency between simulations and observations implies that a galaxy doubles its mass through gas accretion in about 10 Gyr (Bournaud & Combes 2002, Block et al 2002). The source of continuous cold gas accretion can come from the cosmic filamentary structure in the near environment of galaxies. Cosmological accretion in cosmological simulations confirm this gas accretion rate (e.g. Semelin & Combes 2005), and therefore bar reformation.

4 Warps and polar rings

The presence of warps in almost all galaxies (conspicuous in HI-21cm) can only be explained through misaligned external gas accretion (e.g. Binney 1992). The amount required can lead to the reorientation of the angular momentum of the galaxy in 7-10 Gyr (Jiang & Binney 1999). This would correspond to the same amount of gas accretion that can explain bar frequency.

Polar Ring Galaxies (PRG) are composed of an early-type host surrounded by a perpendicular ring of young stars and gas, akin to late-type galaxy disks. Stars in the polar ring have formed after the interaction/accretion event, from the gas settled afterwards in the polar plane. The frequency of PRGs deduced from observations is about 5% (Whitmore et al 1990).

The formation of polar rings can be explained either by gas accretion (Schweizer et al 1983, Reshetnikov et al 1997), or by a galaxy merger (Bekki 1997, 1998). External gas can be accreted either from a passing by companion, or from the cosmic web filaments. Numerical simulations
reveal that it is about 5 times more probable to form a PRG by gas accretion (Bournaud & Combes 2003).

5 Lopsided galaxies

The frequency of asymmetries in galaxies can also help to constrain the gas accretion rate. Peculiar galaxies without any companion are quite frequent, about 50% out of a sample of 1700 galaxies have an HI asymmetric profile (Richter & Sancisi 1994). The asymmetry is even more frequent for late-type galaxies, about 77% (Matthews et al 1998). The asymmetry is also observed in the stellar disk in the optical light (Zaritsky & Rix 1997).

Recently, the amplitude of lopsidedness has been quantified precisely in the NIR distribution (from 150 galaxies of the OSU sample) and compared to what is expected from numerical simulations (Bournaud et al 2005). The $m = 1$ perturbations could be excited by a companion, or during the formation of the galaxy, since they can persist under the form of kinematic waves for quite a long time, but still not sufficient to explain the observed frequency now (Baldwin et al 1980).

It is difficult to explain all lopsidedness through the tidal interaction from companions, since most galaxies are isolated (Wilcots & Prescott 2004), and for those with visible companions, the amplitude of the $m = 1$ perturbation does not correlate with the tidal index (proportional to the mass of the companion and inversely to the cube of its distance). In addition, the amplitude of the $m = 1$ and $m = 2$ perturbations are correlated, and also the $m = 1$ intensity correlates with type, which is not predicted for galaxy interactions.

The cause of the $m = 1$ could then be either a minor merger (no companion is seen), or external gas accretion. Both processes have been simulated, and the amplitude of the $m = 1$ perturbation then quantified, as a function of time (Bournaud et al 2005). It is found that only asymmetric gas accretion is able to reproduce the high frequency of the asymmetries observed, since the result of a minor merger becomes symmetric quite early (see Figure 5). Only gas accretion (here with 4 M$_\odot$/yr) can explain the observed frequency of $m = 1$ and the long lifetime of the perturbation in NGC 1637. A large number, at least two thirds, of strong $m = 1$ galaxies require external gas accretion.

Figure 5: Left: Evolution of $A_1$, the amplitude of the $m = 1$ perturbation, in a simulation of asymmetrical gas accretion. A strong lopsidedness is triggered, even in the stellar component (through star formation), in a galaxy that looks completely isolated. Middle: Stellar image of a simulation of asymmetrical gas accretion, with a rate of the order of 4 M$_\odot$ yr$^{-1}$, which produces a lopsided galaxy quite similar to NGC 1637. Right: NIR map of NGC 1637 from the OSUBGS data, after deprojection. A strong lopsidedness is present in this very isolated galaxy (from Bournaud et al 2005).
6 Environmental effects in clusters

The relative importance of the hierarchical scenario and secular evolution 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.

Although massive galaxies in rich clusters are passively evolving ellipticals, devoid of any star formation, this has not always been the case. Clusters have evolved in a recent past. High resolution images with the HST, followed by spectroscopic surveys, have shown that there exist signs of tidal interaction/mergers in $z=0.4$ clusters. There is a much larger fraction of perturbed galaxies, a larger fraction of late-type and starbursting objects. Rings of star formation are much more frequent than 2-arm spirals (Oemler et al 1997). And it is well known that there is an excess of blue galaxies as a function of $z$ (Butcher, Oemler 1978, 1984).

Moreover $z \sim 0.5$ 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. Star formation was quenched, in these galaxies 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).

Star formation and morphological evolution appear decoupled in cluster galaxies (Couch et al 2001), while star formation is still occurring actively now in groups (Balogh et al 2004). The star formation rate is strongly dependent on the local projected density, star formation is quenched as soon as the density is above $\Sigma = 1$ galaxy/Mpc$^2$, independent of the size of the structure. It is likely that the bulk of the stars now in massive galaxies have been formed in spiral galaxies in groups, before merging into ellipticals.

7 Conclusion

Three main processes have been invoked for the mass assembly of galaxies: monolithic collapse (MC), hierarchical merging (HS) and external gas accretion associated with secular evolution (SE). The MC scenario appears limited at high redshift, involves only sub-components of galaxies and has a limited role, while the two others (HS and SE) compete with comparable weights to galaxy formation.

Observations constrain the relative importance of these processes. The star formation history across the Hubble time, either through the fossil record of present stellar populations, or direct observations of galaxies at various redshifts, reveals that massive galaxies have now stopped their star forming activity, while intermediate-mass spirals are still continuing with an almost constant rate, and dwarf galaxies experience starbursts. The observation of massive galaxies at high redshift is compatible with the predictions of the ΛCDM model of galaxy formation. The observation of the dynamical state of galaxies (bars, spirals, warps, polar rings, $m = 1$ asymmetries) also constrain the importance of external gas accretion, and secular evolution.

The different processes play a different role, according to the environment. In the field, gas accretion is dominant, to reform bars and spirals, to explain warps, polar rings or lopsidedness. In rich environments, the evolution proceeds at a much faster pace, hierarchical merging had much more importance, and secular evolution of galaxies is halted at $z \sim 1$, since galaxies are stripped from their gas, and from their cold filamentary structure, acting as a gas reservoir.
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