Galaxy Dynamics: Secular Evolution and Accretion

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Abstract. Recent results are reviewed on galaxy dynamics, bar evolution, destruction and re-formation, cold gas accretion, gas radial flows and AGN fueling, minor mergers. Some problems of galaxy evolution are discussed in particular, exchange of angular momentum, radial migration through resonant scattering, and consequences on abundance gradients, the frequency of bulgeless galaxies, and the relative role of secular evolution and hierarchical formation.

Keywords. galaxies: abundances, galaxies: bulges, galaxies: evolution, galaxies: formation, galaxies: kinematics and dynamics, galaxies: spiral, galaxies: structure

1. Disk formation and "viscosity"

There are at least three main scenarios invoked for galaxy formation: the first one, inspired by Eggen *et al.*(1962) is the monolithic collapse, where the initial gas clouds collapse gravitationally while forming quickly stars before the end of their collapse, so that they end up with a stellar spheroid. Disks must then form later on, through slower gas accretion. The second is the hierarchical scenario, where the first systems to form are disks (the star formation time-scale being longer than the collapse time). Then the inter-action and merger of two disks lead to the formation of a spheroid. The third scenario, developed in this talk, considers that disks form first, as in the second scenario. How-ever, disks then may evolve without any merger with other galaxies. Their own internal evolution could also produce a spheroid at the center, through secular evolution. This scenario assumes external gas accretion from filaments of the cosmic web (e.g. Kormendy & Kennicutt 2004).

Spontaneously, a disk evolves through its gravitational instability, producing non-axisymmetric features or waves, that will transfer angular momentum. This is equivalent to an effective kinematic viscosity (Lin & Pringle 1987a). The stability of the disk is ensured at small scales by the equivalent pressure, due to the disordered motions, or velocity dispersions. All scales smaller than the Jeans length $\lambda_J = \sigma t_{ff} = \sigma/(2\pi G\rho)^{1/2}$ are stabilised, where σ is the velocity dispersion, and ρ the density. At large scales, the disk is stabilised by the differential rotation, and the subsequent shear. All scales larger than the critical L_{crit} are stable, where $L_{crit} \sim G\Sigma/\kappa^2$, with Σ the disk surface density, and κ the epicyclic frequency. Scales larger than λ_J and lower than L_{crit} remain un-stable, unless the velocity dispersion is increased until $\lambda_J = L_{crit}$: this condition is the Toomre criterion (Toomre 1964). The parameter $Q^2 = \lambda_J/L_{crit}$ must be larger than 1 for stability. From hydrostatic equilibrium in the z-direction, the disk thickness must be $h = h_r \min(1, Q)$, with $h_r = \sigma/\Omega$.

When instabilities occur, they transfer momentum on scale L_{crit}, with time scale Ω^{-1} (or dynamical time-scale); therefore a prescription for effective viscosity is $\nu \sim L_{crit}^2/\Omega^{-1} \sim Q^{-2}h_r^2\Omega$. In addition, it can be shown that, when the viscous time-scale is

of the same order as the star-formation time-scale, i.e. $t_\nu \sim t_*$, then an exponential disk is formed (Lin & Pringle 1987b).

2. Bars and gas flows

Bars are the most frequent non-axisymmetries developed in galaxy disks. 75% of spiral galaxies are barred, when viewed in the near-infrared. They form easily in numerical simulations, even when $Q > 1$. Bars are very efficient to trasnfer angular momentum. They are robust and generate long-lived gravity torques, acting on the gas, to concentrate mass towards the center. The amount of gas driven towards the center can be quantified by observations. It can be shown that the sign of the torques change at each Lindblad resonance, in particular they are negative (with respect to the sense of rotation) inside corotation (CR), and positive outside. The amplitude of the torques depends on the bar strength, and on the phase shift between the gas response and the stellar potential. Inside CR, the gas leads the stars, and this corresponds to the characteristic morphology of dust lanes leading the bar, commonly observed in barred galaxies.

From the near-infrared image, representing the old stellar component, i.e. most of the mass in the visible disk, it is possible to deduce the gravitational potential of the galaxy. From the gas map observed either through HI or CO lines, it is then possible to compute the average torque exerted on the gas at each radius, assuming a stationary state at least for one rotation. These computations have shown that typically in a strongly barred galaxy, the gas may lose 30% of its angular momentum at each rotation (Garcia-Burillo *et al.* 2005). The stellar bar receives the angular momentum lost by the gas, and therefore weakens: the bar is a wave with negative momentum, with most the orbits sustaining the bar with high eccentricity. The absorption of angular momentum makes the orbits rounder and the bar weaker. This can lead to the destruction of the bar (e.g. Bournaud & Combes 2002).

The gas driven towards the center could fuel the supermassive black hole, present in every galaxy with bulge, and trigger nuclear activity (AGN). It is however difficult to find direct evidence of correlation between AGN and bars, since the evolution time-scales are widely different: the dynamical time-scale for the gas to flow to the center, and to weaken the bar is a few 10^8 yr, while the AGN active phase is a few 10^7 yr. To account for the large frequency of bars, in spite of their easy weakening and destruction, another mechanism has to re-form bars: this is done through external gas accretion, which replenishes the disk, and makes it unstable again to bar formation. First gas is stalled outside the outer resonance by the positive torques, when the bar is strong. When the bas is weakened, the external gas can then enter and fuel the disk, intermittently.

There is therefore a self-regulated cycle of bar formation and destruction: the bar forms in an unstable cold disk, rich in gas. The strong bar produces gas inflow, which weakens or destroys the bar. Gas accretion can then enter and re-juvenate the disk, and a new bar form. A few percent in mass of gas infall is enough to transform a bar in a lens (Friedli *et al.* 1994, Berentzen *et al.*1998, Bournaud *et al.* 2002, 2005). External gas accretion is essential to drive the secular evolution of galaxy disks, and to maintain spirals and bars frequent enough in galaxies. The observed bar frequency can be used to quantify the accretion rate (Block *et al.* 2002). The required accretion rate corresponds to the baryonic galaxy mass doubling in 7 Gyrs. Cosmological simulations have recently revealed the importance of cold gas inflow in filaments. The predicted rate of gas accretion is similar to what is required to maintain the observed bar frequency (Dekel & Birnboim 2006).

A consequence of angular momentum redistribution over the disk by the bar, is the formation of exponential disks, with radial breaks, and different slopes in the outer parts.

The break is expected at the outer Lindblad resonance (Pfenniger & Friedli 1991). When several patterns develop in the disk, there could be several breaks at differnt radii. Alternatively, breaks may also be the consequence of gas accumulation, due to external accretion, together with a threshold of star formation in gas surface density (Roskar *et al.* 2008). The galaxy disk then form inside out, and the break moves radially outwards. This is confirmed through numerical simulations, which show how the successive spirals and bars transfer some of the inner stars to the outer parts. Age and abundance gradients can then change suddenly in the outer parts, after the break limiting the location of new star formation. This can explain the frequent observations of these surprising reversals (for instance after a radius of 8kpc in M33, Williams *et al.* 2009).

3. Angular momentum transfers, radial migration

There is a large efficiency in the exchange of angular momentum, by resonant scattering at resonances, due to several successive spiral patterns, as shown by Sellwood & Binney (2002), leading to radial migration of stars and gas (cf Figure 1).

The principle is that, at corotation, it is possible to exchange angular momentum L almost without heating. Assuming a nearly steady spiral wave, at least for a few rotations, there is an energy invariant, the Jacobi integral in the Ω_p rotating frame:

$E_J = E - \Omega_p L,$

and the energy and angular momentum are related by $\Delta E = \Omega_p \Delta L$. To separate energy in the radial motions, defining the radial action J_R, it can be shown that:

$\Delta J_R = \frac{\Omega_p - \Omega}{\kappa} \Delta L.$

This shows that at corotation, where $\Omega_p = \Omega$, changes in L do not cause changes in J_R, i.e. no radial heating. Exchanges of L will be most efficient near CR, and the orbits which are almost circular will be preferentially scattered, as shown in Figure 1. This kind of change in L without heating is called churning by Sellwood & Binney (2002), while the change with increase of epicyclic amplitude, through heating, is called blurring, since it has specific signatures in the stellar orbits. Gas contributes to churning, while it is also radially driven inwards.
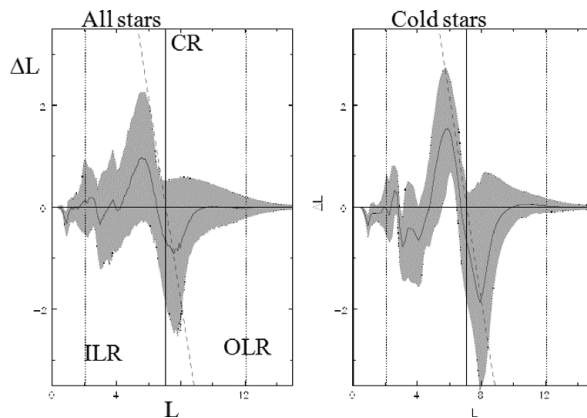

Figure 1. Exchange of angular momentum ΔL, as a function of L, for all stars (left) and only stars with small epicycles (right). The locations of Lindblad resonances ILR, CR and OLR are indicated by vertical lines. The resonance scattering occurs mainly at corotation, from Sellwood & Binney (2002).

In real galaxies, spiral waves are not steady, but transient, and develop with different pattern speeds, so the CR could span a wide range in radii. Radial migration could then involve most of the galaxy disk.

This has important consequences on the chemical evolution, and abundance gradients. The relation between metallicity and age is considerably scattered around a gross trend, as is observed (Shoenrich & Binney 2009). There is also a large scatter in the O/Fe versus Fe/H relation. Radial migration can also produce a thick disk, since stars in the inner disks have higher z-velocity dispersion, due to the higher restoring force of the disk. When migrating outwards, they will feel a smaller restoring force towards the disk, and they will flare. This could explain both the α-enriched and low metallicity property of the thick disk.

The transfer of angular momentum can be multiplied if several patterns exist, with resonances in common. Both bars and spirals can participate to this overlap of resonances. Minchev & Famaey (2010) have shown that due to the non-linear coupling, the region affected by the migration is widened, and the migration rate accelerated by a factor 3. Numerical simulations have confirmed the high migration rate, due to coupled patterns (Minchev *et al.* 2010). The exchange of angular momemtum has now maxima not only at corotation, but also at the OLR. The presence of the gas increases the rate of angular momentum exchange by about 20%. Metallicity gradients can flatten in less than 1 Gyr
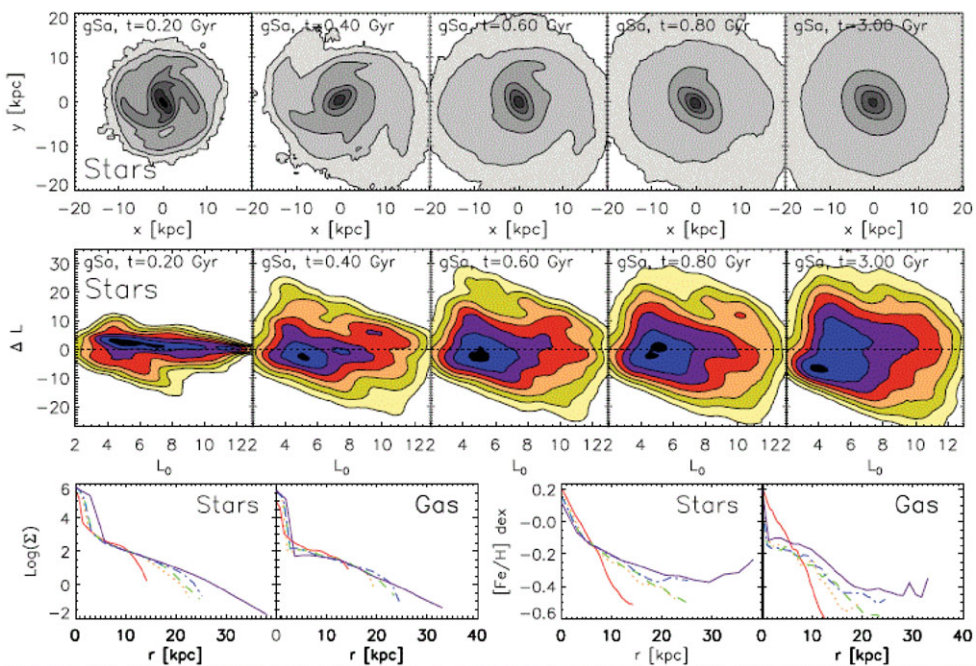

Figure 2. Results of a Tree-SPH simulation, studying the exchange of angular momentum due to resonance overlap of bar and spiral waves. **Top row:** Stellar disk density contours of a giant Sa galaxy in 5 snapshots. **Middle row:** Changes in angular momentum, ΔL as a function of the initial angular momentum, L_0. The locations of the bar CR and OLR are indicated by the dotted and solid lines, respectively. **Bottom row:** The evolution of the radial profiles of surface density (left) and metallicity (right) for the stellar and gaseous disks. The initial disk scale-lengths are indicated by the solid lines. The 5 time steps shown are as in the Top row, indicated by solid red, dotted orange, dashed green, dotted-dash blue and solid purple, respectively, from Minchev *et al.* (2010).

as shown in Figure 2. Again, the migration is the most important, for almost circular orbits. It can explain the absence of clear age metallicity relation, or age velocity relation.

4. Bulge formation

Several mechanisms are invoked to form bulges or spheroids. First, as suggested by Toomre & Toomre (1972), major mergers of spiral galaxies can form an elliptical, with a remaining disk, according to the relative alignment of their initial spins (e.g. Bendo & Barnes, 2000). In minor mergers, disks are more easily kept and progressively enrich the classical bulge. Secular evolution can also form spheroids: bars and their vertical resonance elevate stars in the center into what is called a pseudo-bulge. The latter is intermediate between a spheroid and a disk. Pseudo-bulges are observed more frequently in late-type galaxies. A third mechanism is provided by clumpy galaxies at high redshift. The massive clumps through dynamical friction, quickly spiral in, and form a bulge. Bulges in fact are too easily formed, and the main problem of the hierarchical scenario is to form bulgeless galaxies. These are observed with unexpected abundance, at z = 0.

As for mergers, it is possible that most ellipticals are the result of multiple minor mergers, instead of a 1:1 mass ratio remnant. Numerical simulations have shown that the issue is not the mass ratio of individual mergers, but the total mass accreted, if at least 30-40% of initial mass. A large number of successive minor mergers can form an elliptical galaxy, for instance 50 mergers of 50:1 mass ratio. Given the mass function of galaxies, multiple minor mergers are even more frequent than equal-mass major mergers (Bournaud, Jog Combes 2007a).

The formation of a box-peanut bulge, from disk stars which are in vertical resonance with the bar, i.e. when $\Omega - \nu_z/2 = \Omega_b$, where ν_z is the vertical oscillation frequency, has been known for a long time (Combes & Sanders 1981, Combes *et al.* 1990). During
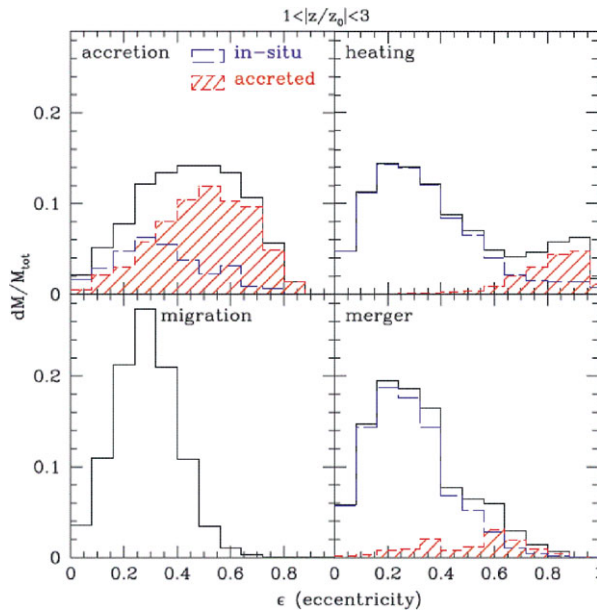

Figure 3. Can the eccentricity distribution of stellar orbits discriminate between the formation scenarios of the thick disk? Here the distributions are compared between four thick disc formation models (accretion, heating, migration, merger), for stars in the range 1.3 scaleheights and cylindrical distance $2 < R/R_d < 3$, from Sales *et al.* (2009).

secular evolution, the resonance can move radially, following the slowing down of the bar, and several peanuts can be formed, larger and larger (Martinez-Valpuesta *et al.* 2006). Even after the bar destruction, the central stellar component will keep its thickness, forming a pseudo-bulge. These spheroids, formed in numerical simulations, correspond perfectly to the kind of pseudo-bulges so frequently observed in late-type galaxies. They have characteristics intermediate between a classical bulge (or an elliptical) and a normal disk (Kormendy & Kennicutt 2004), their main properties are:

• a luminosity distribution μ (in magnitude), with a Sersic index $\mu \sim r^{1/n}$, with $n = 1 - 2$ (exponential disks have $n = 1$, elliptical galaxies $n = 4$ or larger)

• a flattening degree similar to disks, with typical box/peanut shapes, and blue colors

• their kinematics show more rotation support than classical bulges.

Concerning the early evolution of galaxies, their percentage of gas is so high that their disk is unstable and fragments in a few massive clumps. With stars forming in those clumps, this scenario explains the formation of the clumpy galaxies observed at high redshift, which appear as chain galaxies, when edge-on. Numerical simulations then show the rapid formation of exponential disks and bulges, through dynamical friction (Noguchi 1999, Bournaud *et al.* 2007b). The evolution time-scale might even be shorter than with spirals and bars, given the contrast of the structures.

Many spiral galaxies are observed with a thick disk, distinct from their younger thin disk, where contemporary stars are forming. This thick disk could trace some features of the galaxy past formation. At least 4 scenarios have been invoked for the thick disk formation:

• 1) Accretion and disruption of satellites (like in the stellar halo)

• 2) Disk heating due to minor merger

• 3) Radial migration, via resonant scattering

• 4) In-situ formation from thick gas disk (mergers, or clumpy galaxies).

Sales *et al.* (2009) recently proposed that orbit excentricity of stars could help to disentangle among these scenarios.

5. Conclusion

The gravitational stability of disks, the dynamics of spiral perturbations, and the feedback cycle generated may explain the formation of exponential disks, with efficient kinematic viscosity. Angular momentum exchange are also very efficient with bars, which gravity torques drive the gas towards the center, in a few dynamical times. In addition, resonant scattering by spiral waves, constantly re-generated with different pattern speed, are efficient to produce radial migration of stars and gas. When overlap of resonances occurs, between spirals, or between spiral and bars, the migration is strong and spans the whole disk.

If classical bulges and spheroids are commonly the results of mergers, secular evolution can also form the pseudo-bulges, through vertical resonance with the bar. Bulges in early and late-type galaxies could be formed by a combination of these two mechanisms. Presently, it is very difficult to explain the presence of a large number of bulge-less galaxies, the more so as clumpy galaxies formed by gas instabilities at high redshift will also form massive bulges through dynamical friction.

Several scenarios have been invoked for thick disk formation, and a detailed study of stellar orbits could help to discriminate among them.

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Discussion

J. TOOMRE: Are there ways to assess how much mass of gas is flowing in from the cosmic web to replenish a galaxy? What are the signatures of such replenishment of gas?

F. COMBES: It is difficult to find direct evidence, since the infalling gas is diffuse, too dilute to be detected (either as HI atomic gas at 21cm, ionised or molecular gas). Around our own galaxy, high velocity HI clouds have been observed for a long time, and with simple models giving their distance, they would correspond to an infall of a few solar masses per year. Around external galaxies, the search is difficult, by lack of sensitivity. It is possible that the ubiquitous warps in spiral galaxies come from external accretion. A stream of HI gas emission has been observed in the edge-on galaxy NGC 891 up to 25kpc distance.

But indirectly, it is possible to infer how much is required for the spiral maintenance in galaxies, and in particular the bar frequency in late-type spirals. From the observed bar frequency compared to numerical simulations, this gives a doubling of mass of a typical Sb in 7-10 Gyrs, which corresponds to the right order of magnitude of the cold gas accretion in cosmological simulations. Another indirect way is to quantify the frequency of bulgeless spiral galaxies today. If galaxies acquire their mass only through merging, then there should be massive bulges in all galaxies, and it is not what is observed. At least half of the spiral galaxies did not have any major merger in their life, nor a lot of minor mergers, but should have grown through gas accretion.

E. Ntormousi: (About cold flows forming disk galaxies) What is the density / metallicity / speed of these flows? Are they stable to hydrodynamical instabilities? Could they be star-forming?

F. Combes: They are not dense enough to be star-forming. They are low metallicity and they would indeed be unstable to hydrodynamical instabilities.

J. Wolf: Have you examined what happens with 10 1:10 mergers instead at 50 1:50 mergers? Recent work suggests that 1:10 mergers are more common.

F. Combes: Yes, we did explore all these mass ratios. Averaged over the geometrical parameters, 10 1:10 mergers have a remnant quite similar to the 50 1:50 remnant.

A. S. Brun: I did not realize there was so much radial displacement of stars (or the sun). What is exactly the proper motion of stars?

F. Combes: The velocity dispersion of stars is of the order of 30km/s in average, more for the older stars, and less for the youngest ones. However, the migration is done through spiral in (and out) of the orbits, due to exchange of angular momentum, and is equivalent to a radial velocity of 10km/s.

A. Curir: How does the result depend on the concentration of the satellites, since more concentrated galaxies will not be disrupted by tidal forces before the final merger?

F. Combes: We compared the results using satellites having Hernquist's profiles and NFW density profiles, and we did not find significant differences, even if the concentrations of these profiles is noticeable.