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Dynamical Evolution of Galaxies

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Abstract. In this paper, I briefly review some of the dynamical processes involved in the shaping of galaxies, from interactions to the role of supermassive black holes.

Contents

1 Brief introduction

In this course, I will briefly review some issues important in the context of the dynamical evolution of galaxies. A warning should be provided here, as it is difficult if not impossible to truly separate the dynamical and the chemical evolutions in these systems. Star formation, feedback processes are not well understood, but do play a critical role, to say the least, in the building of galaxies. Although I will try to focus the present discussion mostly on the stellar dynamical processes, it is important to keep this in mind. Before starting, I would like to raise two important points in this context. Firstly, the arrow of time is unfortunately not reversible, as the dissipative components (e.g. gas) are intervening in the building of galaxies. Secondly, we should always try to estimate the timescales for the different processes we wish to examine, in order to have a full view of their importance in the global picture.

In the following, I will first briefly describe the cosmological context of galaxy formation and evolution, specifically emphasizing interactions and mergers. I will then focus on the different components of a galaxy (bulge, disk) and examine the processes involved in their dynamical evolution. I will then pass on a short description of density waves, and their role in shaping the central regions of galaxies, to finally conclude with a mention of mechanism linked to the presence of supermassive black holes at the centre of galaxies.

2 Interactions, mergers

Interactions and merging have been very active processes in the past, with e.g. a factor of 10 increase in the number of interacting pairs from $z = 0$ to $z = 1$ (Le Fevre et al. 2000, Brinchman & Ellis 2000). A galaxy at $z = 1$ has about a 50% probability to avoid a major interaction, to be compared with a 15% for a galaxy at $z = 2$. These interactions, and/or merging induce strong changes in the global characteristics of the participating objects (total angular momentum, gas fraction, bulge to disk ratio, ...). In the next paragraphs, I very shortly review attempts at simulating interacting or merging galaxies, and mention a few basic associated dynamical processes. For a more thorough account on the subject, the reader is strongly encouraged to have a look at the existing reviews by e.g. Barnes (1996) or other experts in the field.

2.1 $z = 0$ *observations and simulations*

During a galaxy-galaxy interaction, the tidal potential induced by the first passage of the companion can easily reach 5 to 10% at distances of about 10 kpc from the centre of the primary, this obviously depending on the details of the interaction (e.g. pair mass ratio, orbital characteristics, dark matter distribution, ...) This is a factor of a few larger than the induced perturbation due to a bar in a disk galaxy, which is also more spatially focused. The observed tidal arms is a nice illustration of the strength of these perturbations, as well as of the fragility of galaxy disks.

The first "modern" attempt to simulate galaxy-galaxy interactions can be found in the famous 3 body experiments of Toomre & Toomre (1972) who qualitatively reproduced some of the global features of interacting systems (e.g. M 51, the Antennea - NGC 4038/4039; see also Lynds & Toomre 1976). As simulations improved, details in the observed distribution and kinematics appeared as crucial to properly constrain the initial conditions (characteristics of the parent galaxies, orbital parameters, dark matter concentration; Dubinski et al. 1996, Horellou & Combes 1999). Present simulations include live stellar particles, a treatment of the gas component (SPH, sticky particles), and make use of efficient algorithms which are not dependent on a priori fixed geometry (e.g. parallel tree codes). Besides the numerous papers published by different groups/individuals (e.g. Barnes, Hibbard, Dubinski, ...) on such work, there are well-advertised wep pages presenting these results where the reader can easily dig for further details and nice illustrations[1].

2.2 Dynamical friction and diffusion processes

The trajectory of 2 galaxies can be roughly described via their relative velocity v and the impact parameter b. This provides the associated energy $E = v^2/2$ and angular momentum $L = b{\cdot}v$ per unit mass. Figure 1 summarize the idealized condition for the merging to occur versus E and L. Dynamical friction is however playing a key role here, by imposing a change of velocity as the small companion plunges into the discrete mass distribution of the primary galaxy. This process is classically described via the Chandrasekhar formulae (see e.g. Binney & Tremaine 1987 for a more detailed account). However, this is an approximation which considers an isotropic velocity distribution, a defined maximum for the impact parameter, ignores any deformation of the incoming satellite, and does not take into account the response of the host galaxy. The proper derivation of the merging timescale is therefore often estimated via numerical simulations.

The dynamical friction basically transfer energy and orbital momentum into the internal dynamics of the merging galaxies. In a parabolic

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[1] 2 examples to be found at: http://www.ifa.hawaii.edu/~barnes, and http://www.cita.utoronto.ca/~dubinski

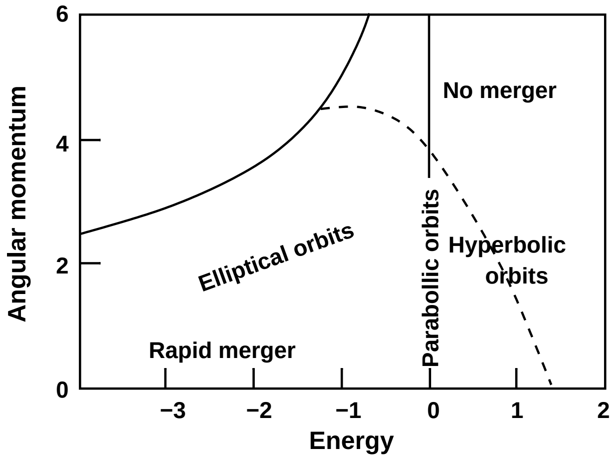

Figure 1: *Galaxy-galaxy interaction according to the initial angular momentum and energy.*

encounter, the merging steps are typically: tidal forces affect the dark matter halos first, which implies a local offset of the galaxy cores from the large-scale potential; the bounded cores are then forced back to the potential well, thus transfering energy from the orbital momentum; the halos are then not following the initial parabola anymore, thus closing on the merging process.

The dynamics of the end-product is then the result of a complex set of mechanisms, difficult to quantify from the sole knowledge of the initial dynamical structures of the parent galaxies. The slow (or sometimes rapid) variation of the potential induced by the interaction implies a loss of the initial values of the energy and angular momentum of the stars. This diffusion acts as a relaxation process, but is usually not completed at the end of the merging. Another diffusion mechanism affects the final distribution function of the merger remnant: phase mixing. In principle, the density in phase space F is constant along an orbit, and is always bounded by its initial maximum value F_{max}. The maximum value of the phase-space density can then only decrease during the merging (ignoring the gaseous component). Only the dynamically cold systems will in fact suffer from a significant decrease of their maximum F_{max} during the merging (Carlberg 1986, Barnes 1992). The merger process should still conserve homology. But the dark and visible matters having different initial distributions will be affected in a different (non-homologous) way. The net result is a differential concentration of the visible matter due to the merging.

Other interesting mechanisms can be traced in the outer faint structures of merger remnants. One well-known signature of a merger can

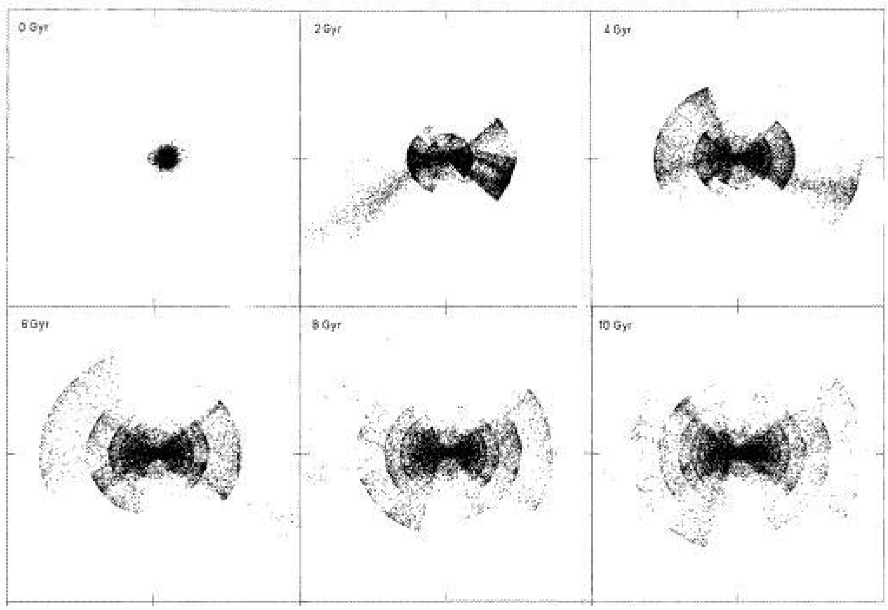

Figure 2: *Snapshots of a numerical simulation showing the phase wrapping process in action, producing shells often observed in the outer parts of early-type galaxies. From Dupraz & Combes 1986*

be observed as the so-called shells often surrounding ellipticals (Malin & Carter 1983). They are explained by a phase wrapping process (Quinn 1984, Dupraz & Combes 1986): a set of stars launched on radial orbits in a potential well will naturally diffuse in radius according to the period of their radial oscillations. The stellar shells are then marking the location of the turnover of these orbits (see also Charmandaris, Combes van der Hulst 2000). As the spatial distribution and shape of these shells depend on the geometry of the potential, these structures have been used as a constrain of the dark matter distribution (Fig. 2).

2.3 The dichotomy in the properties of elliptical galaxies

The modern view of the Hubble sequence of galaxies suggests that transformation occur from late-type (spirals) to early-type (ellipticals), interactions and mergers playing a dominating role in this time evolution. We are now generally thinking of two classes of early-type galaxies with a (diffuse) boundary in luminosity:

- Low-luminosity ellipticals ($M_V > -20.5$): are close to isotropic rotators (said to be "supported by rotation"), have disky isophotes, and a cuspy central density profile.

- Luminous elliptical galaxies ($M_V > -20.5$): they are anisotropic rotators, have more boxy isophotes, and shallow central (so-called core) profiles .

This dichotomy has been discussed by many authors (see Kormendy & Bender 1999 and references therein). Is this the signature of a different merging history (dissipative or not, major or minor)? If we think of elliptical galaxies as made of the orbital bricks constrained by the gravitational potential, we can roughly classify a few building blocks which correspond to the main orbital families: loops - short or long axis -, box, and other species like fishes, pretzels ... During the merging, the fraction of orbits in each of the main families will change. Recent studies using numerical simulations (mainly pure N-body) suggest that high angular momentum orbits are better preserved in minor mergers, which could be linked with low-luminosity ellipticals having higher rotational support (Bendo & Barnes 2000, Cretton et al. 2000). It now possible to analyse the internal dynamics of early-type galaxies using extensive spectroscopic data (e.g. integral field) and state-of-the-art modelling (e.g. Schwarzschild): examples such as the lenticular galaxy NGC 821, which exhibits a distinct disk-like component with a rather low angular momentum in its distribution function, will probably provide key information on the merger history of early-type galaxies (McDermid et al. 2002, in prep.).

The pure N-body simulations mentioned above cannot however account for the very high rotational support of some low-luminosity ellipticals: this hints for the importance of the dissipative medium (gas) in the merging process. This is also indicated by the presence of central dynamically decoupled structures in some ellipticals, which are thought to be the result of central gas accretion followed by star formation (Fig. 3). The presence of gas implies a non-reversibility of the time arrow. The merging of galaxies including gas results in "more-axisymmetric" remnants (Frenk et al. 1988, Dubinski & Carlberg 1991, Dubinski 1994). This can be roughly explained by considering the fate of the gas in such a situation: the torques induced by the varying and non symmetric potential will tend to remove angular momentum from the dissipative component, the potential thus becoming deeper, tending to its axisymmetrization. Note however that the diffusion due to the violent relaxation is similar with and without gas. Finally, the gas can be the source of star formation, particularly in the central region where higher densities can be reached. This, again, may be the origin of kinematically decoupled cores, as observed in about 10% of elliptical galaxies.

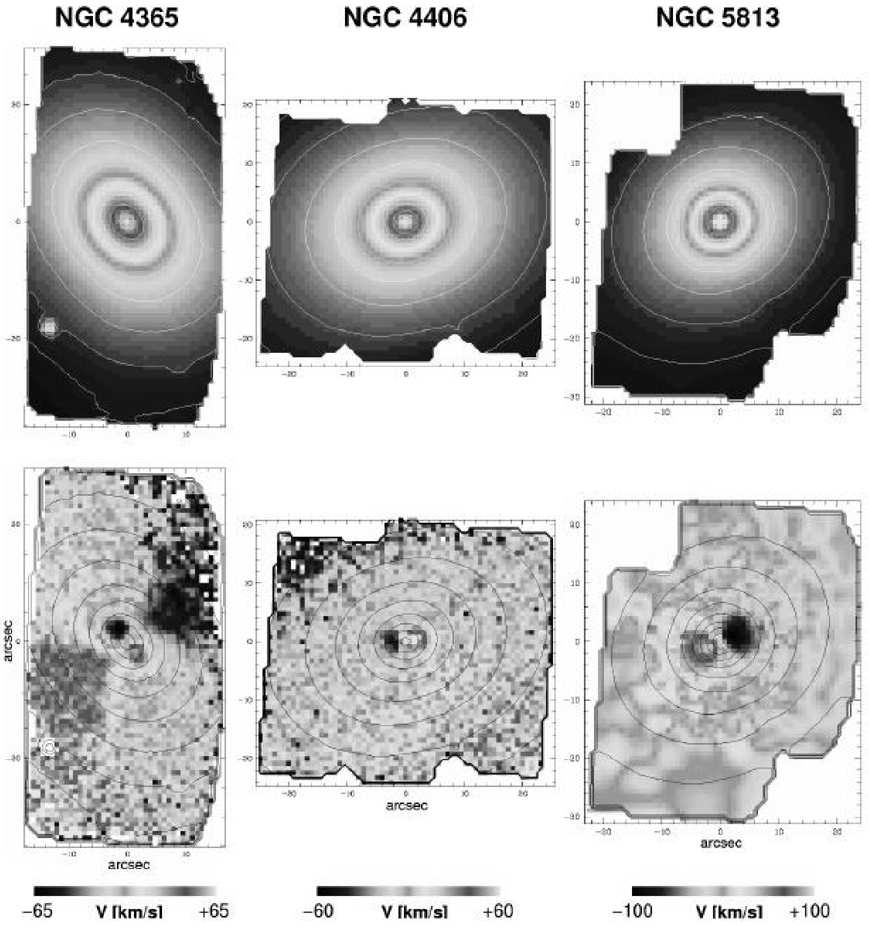

Figure 3: *Three kinematically decoupled cores observed with the integral field* SAURON. *The top panels show the reconstructed luminosity distribution, and the bottom panels present the corresponding stellar velocity maps. The central decoupled system are clearly detected only in the kinematics. They are probably the result of a dissipative merger, which in the case of NGC 4365 occured at high redshift (Davies, et al. 2001).*

3 Processes of Evolution

As we have seen in the previous Section, we expect galaxies to suffer serious changes in their characteristics due to interactions and mergers. Thus we expect galaxies to evolve through the Hubble sequence during their lifetime. It is now interesting to focus more specifically on the different components (bulge, disk, bar, spiral), related to the Hubble classification of galaxies, and mention a few issues regarding their building and evolution. We will then briefly emphasize some processes which affect the internal stellar distribution.

3.1 Evolution of bulges

Bulges are supposed to be well-defined as the central spheroidal components of spiral galaxies. However, it is often difficult to disentangle the bulge from the disk, as parametric forms for their respective surface brightness distribution have to be assumed. In the central few hundreds of parsecs, the spheroidal component merges with the disk and the core region requiring again a priori assumptions about their fractional distribution. Surface brightness of bulges have been well studied with now a census on a generalized projected radial luminosity distribution given by the Sersic law ($\mu(R) \propto R^{1/n}$). See details in Michard 1985, Andredakis 1995, Peletier & Balcells 1996, 1997 and Peletier et al. 1999. There seem to be a trend of bulges having a larger Sersic exponent n in earlier type galaxies, following the common knowledge that surface brightness profiles in early-type galaxy are close to de Vaucouleurs' law ($n = 4$) and late-type spirals close to exponentials ($n = 1$). As shown by Peletier et al. 1999, bulges in early type spirals (S0 to Sb) have very tight colour-colour diagrams hinting for a small spread in age. The central luminosity slopes and colours of bulges were studied by Courteau et al. (1996), Carollo (1999 and references therein). The latter work showed evidence for exponential bulges to have a lower and bluer central surface brigthness.

Are exponential really younger, as suggested from their bluer central colours? Are bulges in early-type galaxies similar to elliptical galaxies? The mentioned observations hint for a formation of the late-type bulges from the disk, and not from bulges with high n exponent. This also suggests that interactions and/or mergers may play a role in moving a bulge along the Hubble sequence going from low to high n (from the right to the left in Fig. 4). This has been studied in the specific context of bulges evolution by Aguerri et al. (2001). These authors showed via numerical simulations that indeed the Sersic exponent n of the bulge increases via the accretion of small satellite onto the parent galaxy (Fig. 5). However, this probably does not catch all the details involved in the making of

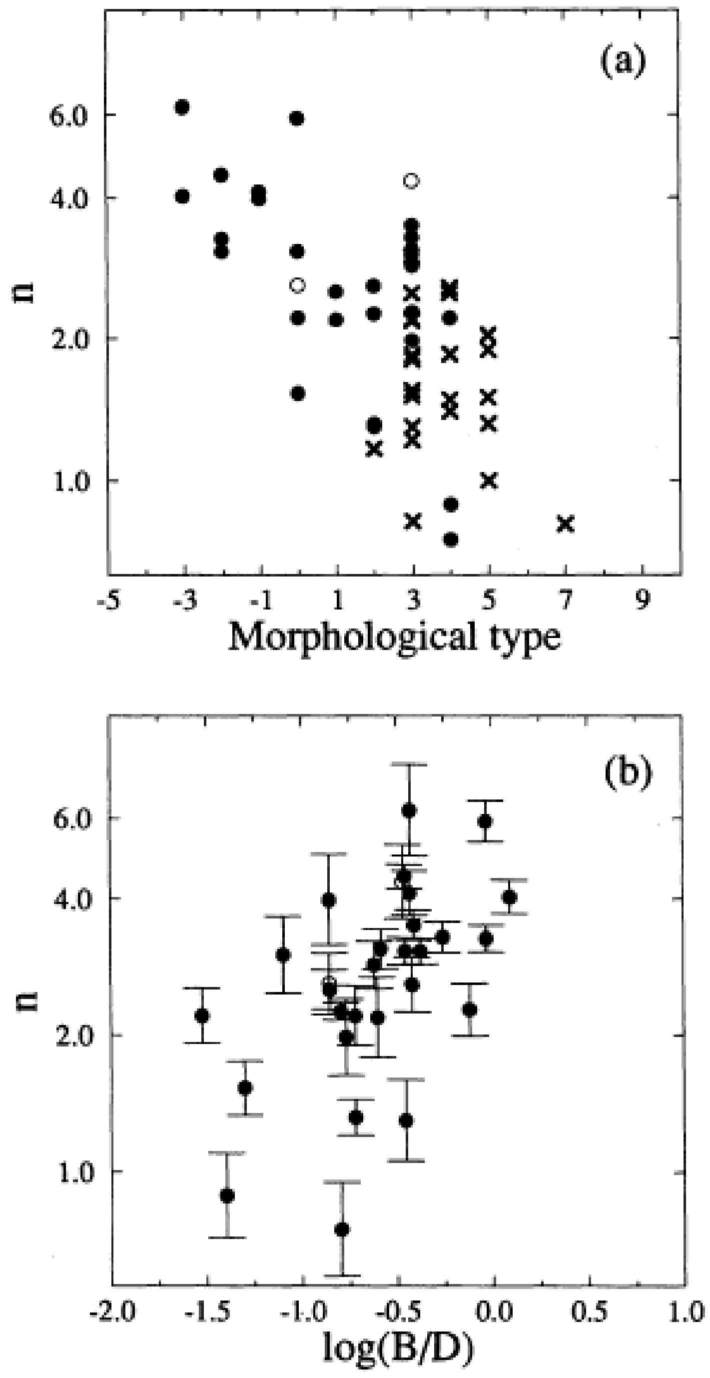

Figure 4: *The Sersic exponent versus the morphological type (top) and the bulge to disk ratio (bottom) showing a trend to higher values of* n *for earlier types. From Andredakis (1997), see also Andredakis et al. (1995).*

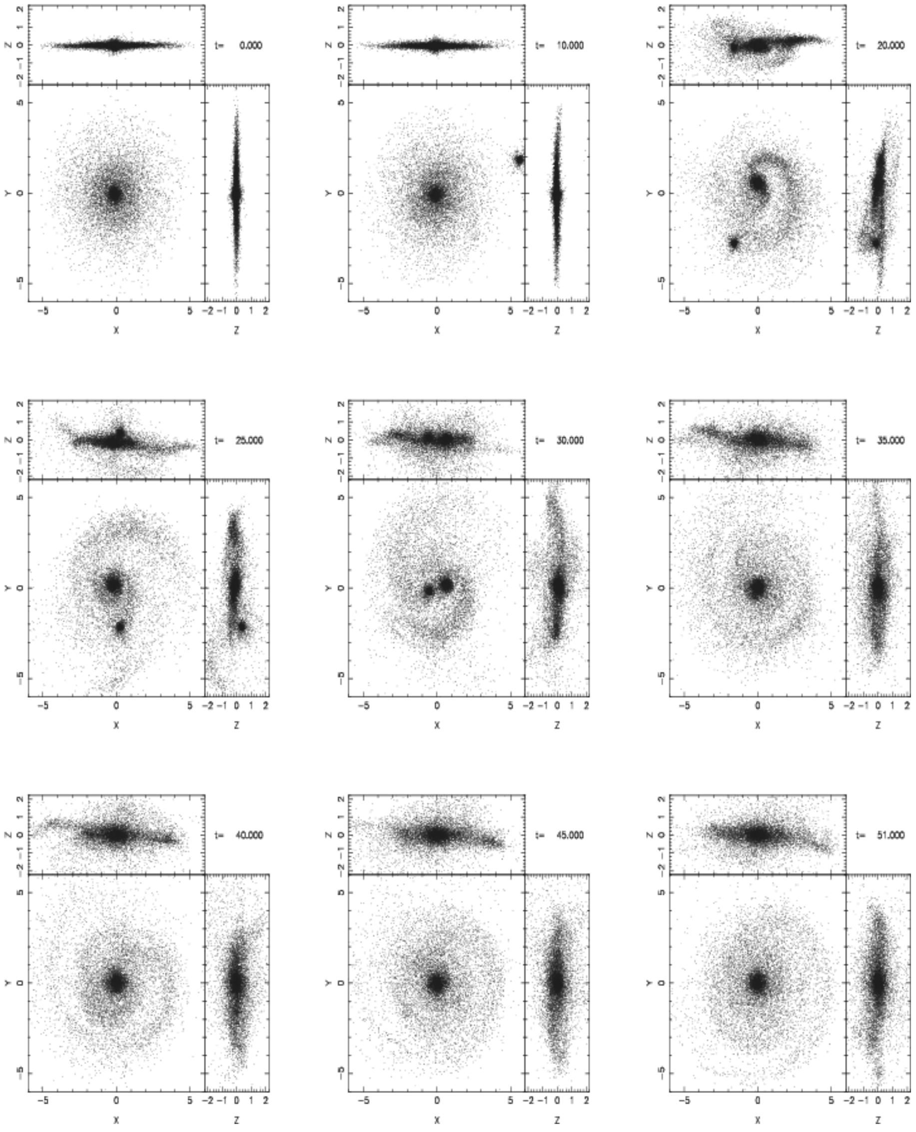

Figure 5: *Snapshots of an N-body simulations showing the accretion of a small satellite. The Sersic profile of the resulting bulge has an increased n exponent.*

early-type bulges, as gas (and stellar formation, as well as feedback) must be taken into account.

3.2 Heating the disk

Disks, being dynamically much more sensitive to perturbations, will also more easily evolve through interactions. Satellite on prograde and retrograde orbits will heat the disk in a different way (e.g. Aguerri et al. 2001). But overall the radial and vertical scales tend to increase, although the ratio of the two, R_e/h, does decrease during the process. Vertical heating can also be witnessed in the so-called peanut galaxies (e.g. NGC 128), which exhibit stars orbiting at large distances above the equatorial plane. However in this case, the source of the heating is associated to an instability linked with Lindblad resonances in a barred galaxy (Combes et al. 1990).

Other important mechanisms inducing the heating of disks are worth mentioning here, and particularly the vertical and radial diffusions of stars. It is known since the 50's that the dispersion σ of stars in the disk of our Galaxy is correlated with their spectral type (Parenago 1958). Eggen, Lynden-Bell & Sandage (1962) suggested that this was due to a decrease in time of the turbulence of the gas from which the stars form. But this was found later to be inadequate to explain the observations. Modern data show a dependency of σ as $t^{0.33}$ starting at values around 8 km/s (Binney, Dehnen, Bertelli 2000). The colour dependency shows a dispersion σ which slowly rises from about 20 km/s to 50 km/s for $B-V$ of 0 and 0.6. For $B-V > 0.6$, σ is roughly constant.

The first intuitive idea to explain these trends is to consider the perturbations due to e.g. molecular clouds, globular clusters (Spitzer & Schwarzschild 1953). The disk stars occupy a limited region of the phase space, and will be diffused by the passage of such objects through the disk. But following this suggestion, $\sigma \propto t^{\beta}$ with $\beta \sim 0.25$ too small to account for the observations (Jenkins 1992). The efficiency of such a process also diminishes with time (Lacey 1984) and the anisotropy σ_R/σ_z is expected to converge to values of about 0.8, much too high compared to the observed one (~ 0.6). Another scenario requires spiral density waves (Sellwood & Carlberg 1984), and the locking into a resonance (Dehnen 1998). The diffusion in the vertical direction is more efficient in principle as the dynamical timescales is shorter and the vertical frequency is a strong function of z. The effect of radial phase mixing can be estimated by deriving its characteristic timescale $\sim 2\pi R/\sigma_0 \sim 5$ Gyr.

If Δ represents the typical radial migration of a star born at a certain radius R, the absence of a correlation between age and metallicity requires Δ to be large enough as compared to R. We can estimate the radial migration of stars expected from their epicycle motion: $\Delta \sim \sqrt{2}\sigma_u/\kappa$, where κ is the radial epicyclic frequency (see next Section). For the old stars in the disk of our Galaxy, $\Delta \sim 1.3$ kpc, much too small to explain the observations. In this context, how can we explain the radial migration of stars, or the change of angular momentum L? This has been recently reexamined by Sellwood & Binney (2002) who claim that a change of 50% can be induced via the resonances linked to a spiral density wave. The basic idea here is that a change in angular momentum ΔL can be expressed as a change in energy ΔE when considering the invariance of the Jacobian (the spiral having a pattern speed Ω_p). Then the change in the radial action ΔJ_R is directly proportional to ΔL via the equation: $\Delta J_R = \Delta L \times (\Omega - \Omega_p)/\kappa$. There is therefore an exchange between J_R and L except at corotation. The distribution of L would not be globally affected by this process but individual stars would still migrate and diffuse radially, which will smooth out age or metallicity gradients.

Finally, dynamical instabilities are playing an important role in the evolution of galactic disks. When deriving the condition of stability, one should always remember to take into account the gaseous component which may render a disk unstable. Instabilities are one key point into the regulation of star formation in disks, but this is out of the scope of this course, and I refer the reader to classical writings such as Binney & Tremaine (1987) and Bertin (2000) for details. I will turn now to the role of density waves in the central regions of galaxies, by first writing a small introduction on the epicyclic motions and resonances in disks.

4 Density waves, and central evolution

Density waves are ubiquitous in galaxies, in the form of spirals, bars, lopsidedness and warps. Modern photometry and spectroscopy provide ample evidence for the importance of such structures in the context of the overall evolution of disk galaxies. Torques induced by density waves imply a redistribution of the dissipative component (gas, dust), and angular momentum is transfered. Star formation is then often associated with crowding regions or shocks, in e.g. spiral arms and rings. Nuclear starbursts may be triggered by the accumulation of gas at the centre of the potential well, via inner density waves. Although there is presently an active debate to know whether or not there is a causal link between e.g. nuclear activity (AGN) and central bars or spirals (see e.g. the Proceedings of the AGN conference 2002, Paris). In any case, secular evolution of disks due to density waves does occur, but the details on how the structures and the internal dynamics are affected still requires some more theoretical and observational inputs. In the following, I provide some basics concepts which are useful in this context.

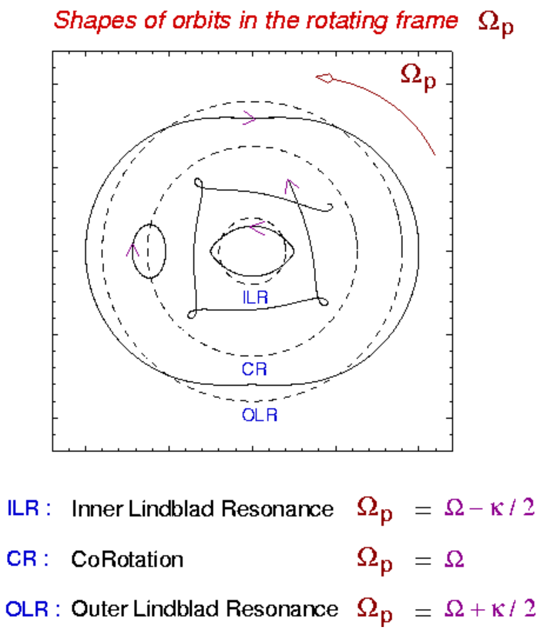

Figure 6: *Shapes of the resonant orbits in a disk, within a reference frame rotating with a pattern speed Ω_p, in the context of the epicycle approximation. Extracted from Combes (2001).*

4.1 The epicyclic approximation

Circular orbits can be used as zeroth order approximations for orbits in the equatorial plane of a thin disk. The first order terms can easily be evaluated by linearizing the equations of motion in that plane. Starting from the zeroth order equations, namely $R = R_0, \ddot{R} = 0$, and adding a first order perturbation in the form $R = R_0 + \delta R, \phi = \phi_0 + \delta\phi, z = \delta z$, we easily find a time dependence given by $\delta R = \delta R(t_0) \cos\left[\kappa\,(t - t_0)\right]$, with κ expressed in terms of the first and second radial derivatives of the potential $\Phi(R, z)|_{z=0}$. This is the equation of an harmonic oscillator with the frequency κ. The same process leads to a similar equation for $\delta\phi$ (with the same frequency κ). The combined motion corresponds to a retrograde epicycle around the guiding center of the circular motion (see Dehnen 1999 for an alternative view on Lindblad's epicycle theory). The shape of the (first order) orbits at a certain radius will then depend on the ratio κ/Ω where $\Omega = V_c/R$ is the circular frequency: when this ratio is an integer m, the orbits are periodic (closing after m epicycles, Fig. 6). With the addition of a density wave with a pattern speed Ω_p, the potential stays constant only in a frame rotating with the wave. In this rotating frame, the important quantity which decides on the shape of the orbit then becomes $\kappa/(\Omega - \Omega_p)$. The resonances are thus located at radii where this ratio takes integer (m) values: $\Omega_p = \Omega + \kappa/m$. This is where the disc potential (with its natural frequency κ) and the wave (of angular frequency Ω_p) may interact. The most important are the Lindblad Resonances (LR; the Inner LR or ILR for $m = 2$, and the Outer LR, or OLR for $m = -2$) and the Corotation Resonance (CR) where $\Omega = \Omega_p$ $(m \to \infty)$. At the resonances, the (linearized) orbits are closed in the frame rotating with the wave, thus defining the different families of orbits from which the skeleton of the system is built.

4.2 Spirals, bars, ...

A different way to look at this, is to take the case of $\kappa/\Omega = 2$ for which the approximated orbit is close to an ellipse. Therefore, orbits in such a simplified system can always be considered as an ellipse with a precession rate given by $\Omega - \kappa/2$ (when it is zero, the precession rate is null, and the orbit is closed). If this precession rate is constant throughout the disk, any configuration of these ellipses (originally aligned or not) will be rigidly rotating at exactly this rate. Otherwise the configuration at $t = 0$ will be differentially modified. This is the classical (although far from really valid) view for understanding structures such as spirals or bars. As self-gravity and self-consistency is introduced into the picture, we must turn to a more realistic description which includes e.g. a linearized form of the Boltzmann equation ($df/dt = 0$ where f is the purely stellar distribution function). This allows to determine the characteristics of the pertubations which can propagate in the gravitational potential of the disk, via a dispersion relation (as in e.g. plasma physics). The parameters coming from the potential are Ω, κ, μ and σ_R, the circular and radial epicycle frequencies, the surface density and the radial dispersion respectively. The parameters of the perturbation, expressed in the shape of a wave $\delta\Phi(R, \phi, t) \propto \exp\left[i\left(\omega t - m\phi - S(R)\right)\right]$ are then ω, k and m, where k is the wave number (radial derivative of S). The dispersion relation can then be solved for some given potential: the disk plays the role of a cavity within which perturbations can propagate. The same approach leads to a different dispersion relation for a gaseous component, where the dissipative property is expressed via the sound speed v_s (replacing a term in the stellar dispersion relation containing the dispersion σ_R). The main question is then to find out not only which waves can propagate, but which can really play a significant role, via e.g. amplification of small pertubations. Again, a more thorough description of such processes is provided in e.g. Binney & Tremaine (1987) and Bertin (2000).

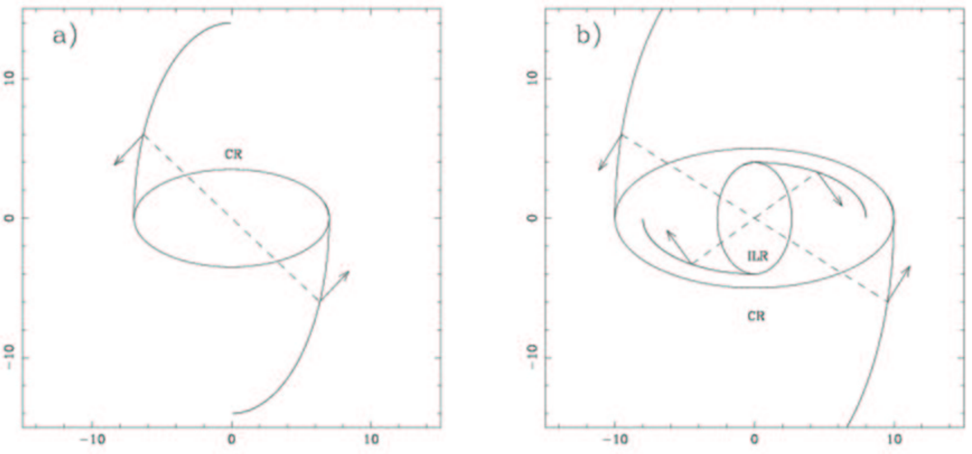

Figure 7: *Gravity torques due to the presence of a bar exerted on the gaseous component. Extracted from Combes 2001.*

4.3 Resonances and rings

One interesting consequence of the presence of a tumbling perturbation in a disk is the torque induced by the non-axisymmetric component onto the dissipative component. A good account of this process, which implies transfer of angular momentum throughout the disk, is provided by Combes (1994, 2001) in the context of bars. Fig. 7 provides a rough description: depending on where the gas originally lies with respect to the resonances (CR, ILR, OLR), it acquires or loses angular momentum. The real story is slightly more complex, but it gives a first taste of the fate of the gas within such a potential: it will be significantly radially redistributed, and shock fronts or regions devoid of gas can be created (see details in the simulations by Athanassoula, 1992). Resonances do play a critical role here, and it is therefore a rather natural thing to associate observed structures such as rings, disks cut-off and other prominent features with the existence of a "beating pulse", the pattern speed of a tumbling system.

It is now clear that such signatures do indeed reflects the evolution of a disk galaxy under the influence of e.g. a bar (see van den Bosch & Emsellem 1998 for a "cute" illustration). A more general study by Seifert & Scorza (1996) showed that a significant fraction ($\sim 60\%$) of S0 galaxies contain two embedded disks: an outer (main) disk with an inner cut-off, and an inner disk. This was confirmed by high resolution HST images which revealed very thin disks in the central kpc of early-type disk galaxies. This is surprisingly similar to the fraction of lenticular

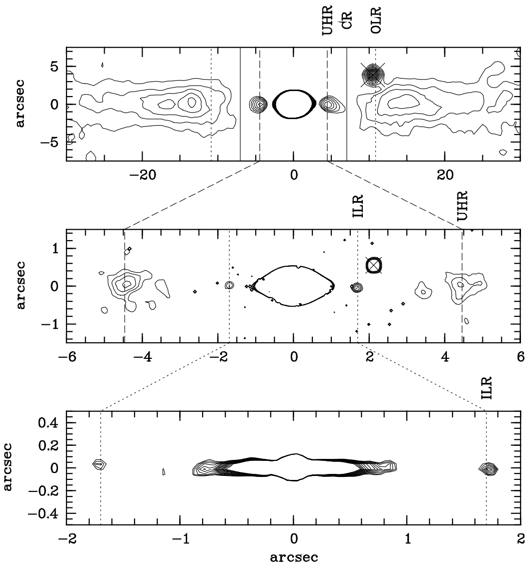

Figure 8: *Unsharp masking of various images of the lenticular galaxy NGC 4570, showing the location of infered resonances due to the presence of a tumbling potential (van den Bosch & Emsellem 1998).*

galaxies hosting a bar. In the case of the Sombrero galaxy (M 104), the double disk structure was claimed to originate from bar driven secular evolution, the inner disk being formed within the ILR of the bar (Emsellem 1995, see also Emsellem et al. 1996, Emsellem & Ferruit 2000). For early-type disk galaxies, such a scenario seems to be supported by several studies (Scorza & van den Bosch 1998; Baggett, Baggett & Anderson 1998). If the disk hierarchy reflects the existence of resonances, these are also often emphasized by gas and stellar rings (at the OLR and Ultra Harmonic Resonance in the case of M 104). Rings are indeed very common signatures of bars (see Combes 2001, Buta & Combes 2000).

4.4 Toward the centre: inner bars

In some cases, the inner disk can decouple from the outer part, and a secondary bar can form (Shlosman, Frank, & Begelman 1989). Double barred galaxies are now well studied (photometrically), and preliminary statistics indicate that at least 25% of barred galaxies host an inner bar (Erwin et al. 2001). We know that primary bars are efficient at concentrating the gas in the central region (Sakamoto et al. 1999). Secondary bars could then take over and fuel the central 100 pc, although no strong dynamical evidence has been presented yet. In this context, we recently obtained the stellar kinematics of 4 active galaxies (central starburst and/or Seyfert), 3 of which are double barred. In these 3 galaxies, the stellar velocity dispersion profiles exhibit a significant but unusual drop at the centre: evidence for the presence of a cold component (Emsellem et al. 2001). We interpreted this as recent gas accretion triggered by the inner bar, and subsequent formation of an inner stellar disk (Wozniak et al. 2002, in prep.). More recently acquired data will help to extend the sample to understand if there is indeed a link between the central activity and the inner bar.

Studies on samples of disk galaxies tend to give slightly different answers (Ho, Filippenko & Sargent 1999; Knapen et al. 2000), although the recent study by Knapen et al. indicate a higher fraction of bars in Seyferts ($79 \pm 7.5\%$) than in non active galaxies ($59 \pm 9\%$). It seems that even if there is a tendency for Seyferts to be more barred than non active galaxies, it is a *weak trend.* As emphasized by Combes (2001), this is not at all surprising, since there are very different timescales involved: gas accumulation driven by the bar, secondary bar formation, star formation, AGN duty cycle, dynamical evolution including the possible destruction of the bar due to central mass accumulation...

4.5 Inner spirals

A recent addition to the usual suspects is the loss of angular momentum by inner trailing spirals. Such structures are often observed in spiral galaxies where resolution permits (Regan & Mulchaey 1999). These are low amplitudes modes however, which does not favour an significant central fueling rate, and these may just be driven by a mildly triaxial tumbling potential. Inner spirals however require a cuspy mass distribution in order to be trailing and drive gas inwards to the nucleus. One strong inner gas spiral has been observed in the early-type galaxy NGC 2974 (Emsellem & Goudfrooij 2002). The spiral ends outside its ILR, which implies that these do not correspond to the bar driven acoustic waves described by Englmaier & Shlosman (2000). In fact, a more study shows almost unambiguously that this inner spiral is associate to an inner bar with an extent of only ~ 400 pc (Emsellem & Goudfrooij 2002). The inner gaseous spiral in NGC 2974 is a rather unique case, although a larger observing campaign using the same techniques is on-going.

4.6 $m = 1$ modes

Lopsided distribution have long been ignored, but are now more often studied theoretically, and looked for in galactic central regions (see Combes 2001 and references therein). The short dynamical timescales in the central kpc of galaxies seem to favour the hypothesis of strongly lopsided distribution to be true $m = 1$ modes. These modes can often be superimposed on $m = 2$ bar modes. One illustration of this is the

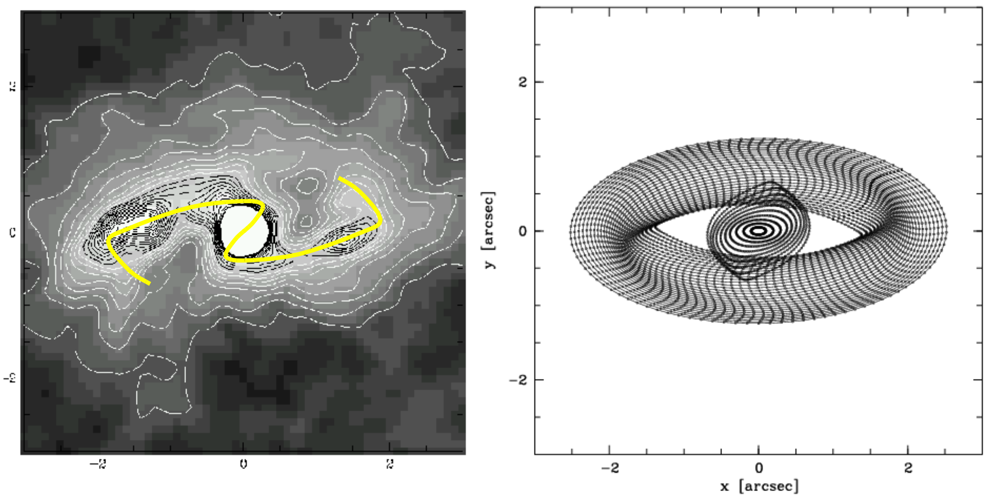

Figure 9: *The inner gaseous spiral in NGC 2974. Left panel: the HST narrow band [NII]/Hα image. Right panel: orbits derived from a model of NGC 2974 perturbed by a weak but fast rotating bar perturbation (Emsellem & Goudfrooij 2002).*

double-barred galaxy NGC 3504. The K band adaptive optics image (courtesy of F. Combes) shows a very strongly asymmetric light distribution. At visible wavelengths, a one arm spiral is revealed by the HST/WFPC2 F606W image. We have observed this galaxy using the integral field spectrograph `OASIS` at CFHT, and determined the two-dimensional stellar and gas distribution and kinematics. The spiral arm is strongly emphasized in the emission line maps, except in the higher density [OI] line, the distribution of which seems to bridge the inner end of the spiral to the nucleus (Fig. 10). In fact, detailed examination of the central `OASIS` spectra reveals the presence of a blueshifted wing in all emission lines including the forbidden ones. We interpret this as evidence for nuclear inflow, possibly driven by the $m = 1$ mode.

4.7 Keplerian modes

In a keplerian potential, $\Omega = \kappa$, which implies that the precession rate of the $m = 1$ orbits is zero at all radii. A set of such orbits could then keep their alignement with time. In a marginally self-gravitating disk, gravity could act to compensate for the non zero precession rate. This seems to be the case for the double nucleus of M 31, in which the offcentred peak could be explained by the orbit crowding (see Bacon et al. 2001, and references therein). This sets a limit on the relative mass of the nuclear disk, which should be between 20 and 40% of the

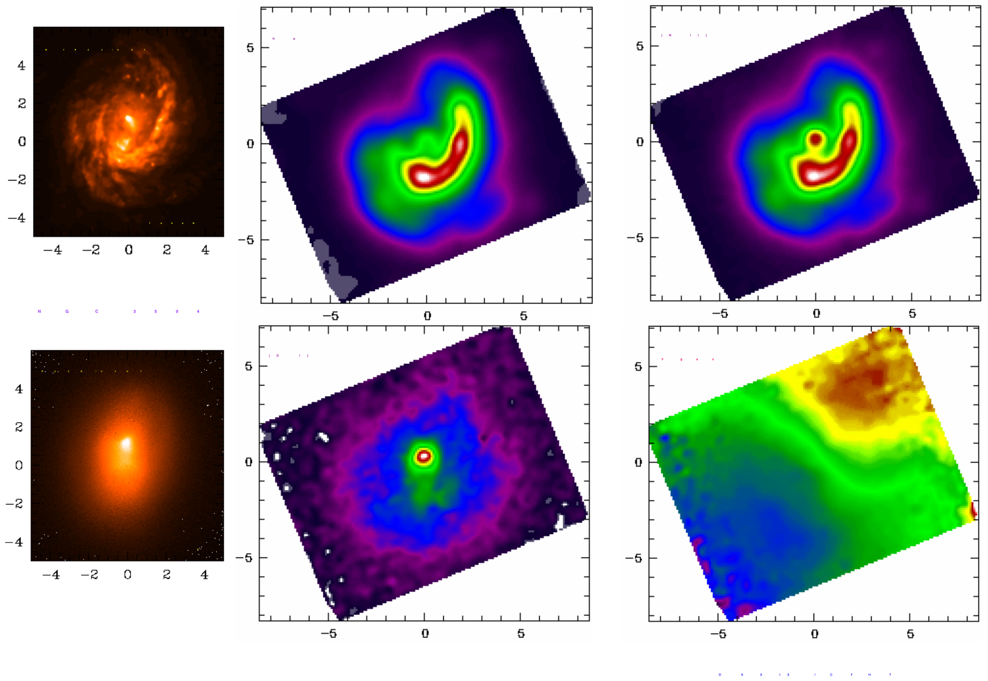

Figure 10: *An example of an* $m = 1$ *mode - The central 800 pc of NGC 3504. Top left panel: HST/WFPC2 F606W image. Bottom left panel: PUEO/CFHT K band image (FWHM* $\sim 0\farcs15$*). All other panels: OASIS/CFHT maps of H*α *(middle left), [NII]*λ*6583 (middle right), [OI]*λ*6300 (bottom left) and mean velocity (bottom left).*

central dark mass. The nuclear disk of M 31 could have been formed relatively long ago by gas accretion triggered by a tumbling potential. In fact, several pieces of evidence support this hypothesis: M 31 is very probably a barred galaxy (Berman 2001), and the inner dust structures are consistent with being trailing spiral arms nearly reaching the nucleus. There is finally a hint of a recent but limited episode of star formation at the very centre of the nucleus. The $m = 1$ mode could then be the result of either a natural instability, or a relatively recent gas cloud infall. As a concluding remark of this rather heterogeneous section, I would like to emphasize the difficulty of separating the role of internal secular evolution and other environmental effects (interaction). This is well illustrated in the cases of the Milky Way and M 31, both exhibiting a main bar (e.g. M 31 - Bermann 2001), and signatures of interactions (see e.g. Ibata et al. 2001).

5 Roles of black holes

This final section is introducing the role of supermassive black holes in the dynamical evolution of galaxies. Obviously the radius of influence of black holes is small compared to the large-scale structures of galaxies. For that reason, but also because of the dynamical timescale, we expect to observe the signature of their presence only in the central 100s of pc at most.

5.1 Cosmological context

The present debate is not much acting on the question of whether nearby galaxies host massive black holes or not, but more on the working of an estimation of their demographics, their origin and evolution. At what redshift does the seed of a black hole form, and how much of its mass did it accrete since then? Recent analytical models, made in the context of a hierarchical universe assume an origin of black holes at high redshift (e.g. Heahnelt & Kauffman 2001, and references therein).

5.2 Binary black holes

Following the merger tree of a present galaxy, we would witness the merging of galaxies containing seed black holes. The mass of the resulting central dark object would then correspond to the sum of the two parent black holes (if a hard binary forms; note that in a system of three black holes, a sling-shot ejection of one of them can easily occur), plus some (gaseous?) accreted material. After the merging process is completed, nuclear black holes could continue to acquire mass via gaseous or stellar fuel (see Combes 2001 for a detailed description of the main processes and their timescales). Black hole binaries are certainly not just a mere fantasy, as witnessed by e.g. double AGN (Owen et al. 1985), but it is still difficult to assess they demographics. See the review by Merritt and other contributions in the Paris AGN Conference (2002, in press) for further details.

A number of simulations following the merging of two galaxies, each containing a supermassive black hole, have been performed (e.g. Milosavljevic & Merritt 2001, and references therein). Although still far from representing real cases, these simulations do emphasize the main stages of the merging process: first approach of the two galaxies, effect of the dynamical friction, creation of the black hole binary, hardening of the binary, final collapse with emission of gravitational radiations, merging of the two black holes. One important consequence of such a process is the influence of the binary onto the central dynamical structure of the resulting galaxy. Stars getting too close to the binary may be ejected via a sling-shot effect. This creates a so-called loss-cone, which may be or not replenished with time via diffusion of orbits. The effect of the presence of gas is not well understood in this context. It would however be interesting to constrain more specifically the influence of such a binary to look for specific signatures in the central dynamics of e.g. elliptical galaxies, as emphasized by Milosavljevic & Merritt (2001). There are ongoing experiments to test whether the diffusion of orbits due to a binary black hole could explain the observed dichotomy of ellipticals in terms of their central cusp slopes: giant ellipticals, having a "core-like" central brighness profile, could be the result of such a diffusion (Milosavljevic et al. 2002).

Another interesting effect of the presence of a black hole is the chaotic diffusion induced by the central singularity (e.g. see the review by Merritt 1999). Stars having their orbit passing too close to the black hole may be deflected, a small cluster then being efficiently diffused in phase space. Contrarily to the process of phase mixing, chaotic diffusion is not reversible (meaning, we would need to know the location of each star with infinite accuracy to go back in time to the original cluster). The timescale for such a process is about ten times the dynamical timescale. There is a consequent axisymmetrization of the central dynamical structure. According to the work of Holley-Bockelmann & Richstone (2000), it however only significantly affects stars typically within about 100 pc.

6 Conclusion

In this paper, I have tried to mention a few interesting issues regarding the dynamical evolution of galaxies. It is obviously not complete, and even more importantly, it is probably not reflecting to the truly important processes which were and are shaping galaxies. I therefore strongly advise the reader to have a look at some of the much more thorough papers I mentioned in this manuscript.

As a closing word, I would like to thank the organizers of this Goutelas School, for giving me the opportunity to prepare this course, to enjoy such a beautiful setting, and more importantly to play ”petanque” in an active (but relaxed) atmosphere.

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