Dynamical Evolution: Spirals and Bars

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Abstract. Non-axisymmetric modes like spirals and bars are the main driver of the evolution of disks, in transferring angular momentum, and allowing mass accretion. This evolution proceeds through self-regulation and feedback mechanisms, such as bar destruction or weakening by a central mass concentration, decoupling of a nuclear bar taking over the gas radial flows and mass accretion, etc.. These internal mechanisms can also be triggered by interaction with the environment. Recent problems are discussed, like the influence of counter-rotation in the m=1 and m=2 patterns development and on mass accretion by a central AGN.

1. Bar formation and destruction

1.1. Rapid evolution of disks

Galaxy disks are far from stationary. They are unstable, with time-scales that can be very short according to the radius. This ranges from M yr in the centers to Gyr in the outer parts, According to the environment, companions, mass accretion, etc.. normal modes can be excited. With the mass distribution of normal nearby galaxies, the most rapidly growing mode is the m=2 (spirals and bars). Trailing waves transfer angular momentum to the outer parts, and concentrate the mass. This mass concentration itself changes the development condition of the modes, and weakens them. Alternatively, the disk is heated by waves and the perturbation fades away, until the next excitation.

1.2. Self-regulation

The evolution of the disk is then controlled by recurrent waves, through regulation and feedback processes. One of these is related to gravitational instabilities, suppressed or favored by heating and gas cooling. When the disk is cold (Toomre Q parameter < 1), and therefore unstable to spiral and bar waves, it develops non-axisymmetric perturbations and gravity torques, that transfer the angular momentum outwards. The disk is progressively heated by the waves until the Q threshold is reached. A disk with only old stars cannot cool and will then remain stable, while a galaxy rich in gas will continue to be unstable by gas cooling. Young stars formed out of the gas reform a cool unstable stellar disk.

The gravity torques that drive the gas inwards play the role of a viscosity; the galaxy disk can then be considered as an accretion disk. An exponential stellar disk can then be built, through star formation, if there is approximate
agreement between the two time-scales, viscosity and star-formation (Lin & Pringle 1987). This is the case, since the two processes depend exactly on the same gravitational instabilities.

The radial inflow of gas towards the center produces a mass accumulation, that can destroy the bar. This occurs when about 5% of the mass of the disk has sunk inside the inner Lindblad resonance (Hasan & Norman 1990, Pfenniger & Norman 1990, Hasan et al 1993). In the mean time, such a mass accretion in the center has created a nuclear disk, which may decouple kinematically from the rest of the disk; there can develop either a secondary bar (Friedli & Martinet 1993) or nuclear spirals (Barth et al. 1995, Regan & Mulchaey 1999). Alternatively, the decoupling may not occur, and the central pattern rotates at the same velocity as the extended one (Englmaier & Shlosman 2000). This depends on the equivalent viscosity and star-formation rates (Combes 1994, Sheth et al. 2000). It is possible that the decoupling involves also a warp (Schinnerer et al. 2000a,b).

After a bar has dissolved, the axisymmetric disk is devoid of torques, and the new gas accreted stays in the extended disk. If there is significant accretion with respect to the mass of the disk, the latter becomes unstable and another bar forms. External interactions and mergers can intervene to destroy the disk, but also to replenish it. The main agents to drive matter to the center in galaxy interactions and mergers, are also the bars triggered by the tidal forces.

1.3. Is the bar responsible for the fueling?

There have been several observational works revealing a correlation between nuclear activity and bars (Dahari 1984, Simkin et al 1980, Moles et al 1995). But the correlation is weak and depends on the definitions of the samples, the completion and other subtle effects. Near-infrared images have often revealed bars in galaxies previously classified unbarred, certainly due to gas and dust effects. However, Seyfert galaxies observed in NIR do not statistically have more bars nor more interactions than a control sample (McLeod & Rieke 1995, Mulchaey & Regan 1997).

Peletier et al (1999) have recently re-visited the question, and took a lot of care with their active and control samples. Their Seyfert and control samples are different at 2.5 $\sigma$, in the sense that Seyferts are more barred. They also measure the bar strength by the observed axial ratio in the images. In Seyferts, the fraction of strong bars is lower than in the control sample (Shlosman et al. 2000). Although a surprising result a priori, this is not unexpected, if bars are believed to be destroyed by central mass concentrations (cf section 1.2).

Regan & Mulchaey (1999) have studied 12 Seyfert galaxies with HST-NICMOS. Out of the 12, only 3 have nuclear bars but a majority show nuclear spirals. However their criterium for nuclear bars is that there exist leading dust lanes along this nuclear bar. This is not a required characteristic, since these secondary bars in general are not expected to have ILRs themselves.

2. Lopsidedness, $m=1$ perturbations

The $m = 1$ perturbation is present in most galactic disks (Richter & Sancisi 1994), often superposed to the $m = 2$ ones. These perturbations can be of
different nature and origin, according to their scale (nuclear or extended disk), or whether they involve the gaseous or stellar disks.

Linear analysis, supported by numerical calculations, show that gaseous disks rotating around a central mass, are unstable for low value of the central mass (Heemskerk et al 1992). The instability disappears when the central mass equals the disk mass.

Density waves for $m = 2$ and higher generally use the corotation amplifier, together with reflections at resonances or boundaries, for a steady mode to grow. For $m = 1$ in nuclear disk, the pattern speed is so low that the corotation falls outside the disk. But, due to the special character of $m = 1$ waves, there exists another amplifier: the indirect term (Adams et al. 1989, Shu et al. 1990). This is due to the off-centering of the center of mass. Long lasting oscillations of a massive nucleus have been observed (Miller & Smith 1992, Taga & Iye 1998).

For extended disks, off-centered in an extended dark halo, lopsidedness could survive, if the disk remains in the region of constant density (or constant $\Omega(r)$) of the halo (Levine & Sparke 1998).

In the special case of a stellar nuclear disk around a massive black-hole, it is possible that self-gravity is sufficient to compensate for the differential precession of the nearly keplerian orbits, and that a long-lasting $m = 1$ mode develops, or is maintained long after an external excitation (Bacon et al. 2000). This could be the explanation of the double nucleus observed for a long time in M31 (Bacon et al. 1994, Kormendy & Bender 1999), and for which an eccentric disk model has been proposed (Tremaine 1995, Statler 1999).

In this $m = 1$ mode, the maximum density is obtained at the apocenter of the aligned elongated orbits (see fig [ ]). The pattern speed, equal to the orbital frequency of the barycentre of the stellar disk, is slow (3km/s/pc, fig [ ]), with respect to the orbital frequency of the stars themselves (250km/s/pc in the middle of the disk). The excitation of the $m = 1$ perturbation can then last more than 3000 rotation periods (fig [ ]).
Figure 2. Pattern speed as a function of radius, in units of km/s/pc, for the $m = 1$ mode, between 28.8 and 43.2 Myr of the M31 simulation. The pattern speed slightly slows down with time (from B00).

Figure 3. **top:** Coordinates (X: full line) of the center of gravity of the stellar disk, as a function of time. **bottom:** Intensity of the $m = 1$ (S1, solid line) and $m = 2$ (S2, light line) Fourier components of the potential (more exactly the correps. components of the tangential force normalised by the radial force), for the best fit model of M31 (from B00).
3. Counter-Rotating Components

The phenomenon of counter-rotating components is a tracer of galaxy interactions, mass accretion or mergers. It has been first discovered in ellipticals with kinematically decoupled cores (likely to be merger remnants, e.g. Barnes & Hernquist 1992). It has been observed also in many spirals; either two components of stars are counter-rotating, or the gas with respect to the stars, or even two components of gas, in different regions of the galaxies (Galletta 1987, Bertola et al 1992). In the special case of NGC 4550 (Rubin et al. 1992), two almost identical counter-rotating stellar disks are superposed along the line of sight.

These systems pose a number of questions, first from their formation scenario, but also about their stability, their life-time, etc.. Do special waves and instabilities develop in counter-rotating disks, and does this favor central gas accretion?

3.1. Stability

First, it appears that the counter-rotation (CR) can bring more stability. Even a small fraction of CR stars has a stabilising influence with respect to bar formation \( (m = 2) \), since the disk has then more velocity dispersion (Kalnajs 1977). But a one-arm instability is triggered, for a comparable quantities of CR and normal stars. This comes from the two-stream instability in flat disks, similar to that in CR plasmas (Lovelace et al. 1997). There develop two \( m = 1 \) modes in the two components, with energies of opposite signs: the negative-E mode can grow by feeding energy in the positive-E mode.

A quasi-stationary one-arm structure forms, and lasts for about 1 to 5 periods (Comins et al. 1997). The structure is first leading, then trailing, and disappears. The formation of massive CR disks in spirals has been studied by Thakar & Ryden (1996, 1998).

3.2. CR with gas

The presence of two streams of gas in the same plane will be very transient: strong shocks will occur, producing heating and rapid dissipation. The gas is then driven quickly to the center. But the two streams of gas could be in inclined planes, or at different radii. This is the case in polar rings, discovered in 0.5 % of all galaxies (Whitmore et al. 1990). After correction for selection effects (non optimal viewing, dimming, etc..) 5% of all S0 would have polar rings.

If there is only one gas stream, the problem is more similar to the two-stream instabilities of stellar disks mentioned above. However the gas is cooling, and is not easy to stabilise against \( m = 2 \) components. Both \( m = 1 \) and \( m = 2 \) may be present simultaneously in these systems. This is the case of the galaxy NGC 3593, composed of two CR stellar disks (Bertola et al 1996): in an extended stellar disk, is embedded a CR nuclear disk, possessing co-rotating gas. The molecular component associated with this nuclear disk reveals both a nuclear ring and a one-arm spiral structure outside of the ring (Garcia-Burillo et al. 2000). N-body simulations have shown that both structures can be explained by the superposition of \( m = 1 \) and \( m = 2 \) in the gas component, the ring being...
formed at the ILR of the bar (fig. 4). In the $m = 2$ pattern, two counter-rotating bars develop (fig 5).

4. Conclusions

Galactic disks are not stationary, they evolve greatly on time-scales of the order of a few dynamical times. In normal disks, there is a preponderance of $m = 2$ spirals and bars. Spirals are the most transient features, but bars also come and go, and several bar episodes could occur in a Hubble time.

According to the mass concentration in the disk, a secondary bar can decouple and rotate with a higher pattern speed. This is important for the ultimate fueling of gas to the nucleus. Observational evidence of correlation between nuclear activity and bars is still controversial. It might be a question of spatial resolution, or the fact that bars are destroyed by massive central black holes.

Lopsidedness is also wide-spread in galactic disks, but much less studied. The nature and origin of the $m = 1$ waves are diverse, either particular to a purely gaseous disk, or a nuclear stellar disk. They could be slowly damped modes (excited by companions), or two-stream instabilities in counter-rotating systems. There is also the special case of rapid off-centring instabilities (oscillations of the center of mass), or nearly keplerian eccentric disks near a central massive black hole.
Figure 5. Pattern speed as a function of radius, in units of 100km/s/kpc, for the $m = 2$ mode (top), and the $m = 1$ mode (bottom), for the NGC 3593 simulation (from G00).

Non-axisymmetric perturbations are transferring angular momentum outwards, and result in rapid evolution of galactic disks. It is likely that continuous disk reformation occurs all over the Hubble time, through mass accretion.

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