FORMATION OF RINGS BY BARS AND TIDES

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Recently many CO distributions in the shape of rings have been uncovered. What dynamically can we learn from these structures? After a brief point on recent observations, I will review the dynamical mechanisms to form rings.

I-Observations

Various types of rings

Several structures are gathered under the same name of rings, and their origin could be very different.

- *First*, can be distinguished the "ring-galaxies", of which the Cartwheel is the prototype. This ring-phenomenon has been simulated by Lynds and Toomre (1976) and Theys and Spiegel (1976). This peculiar morphology is due to all matter, stars and gas, participating into a ring density wave after the nearly head-on collision with a small companion.We will not be concerned by this type of ring here.
- *Second*, can be distinguished stellar rings inside the disk, sometimes 2 or 3 are present at different radii: nuclear rings, inner rings and outer rings.These are frequently associated with bars (Buta 1987). The positions of the rings, when multiple, are compatible with their being at Lindblad resonances of the bar.
- *Third*, gaseous rings can exist without anything conspicuous in the stellar component. This is the case in our own Galaxy for instance (molecular ring between 4 and 8kpc), but also in some Sb-type spirals like NGC2841, NGC7331, M31, ...

Properties of the rings

Nuclear rings and inner rings correspond to concentration of young population: they represent maxima of the gas surface density, with active star-formation (Hα, radiocontinuum emission). Nuclear rings are particularly contrasted: they are well-known to shelter "hot spots", which are very active ionised regions. The outer rings are not so active in general, their light is diffuse, coming from old stars and only atomic gas is tracing them.

The position of nuclear rings usually coincide with the turn-over of the rotation curve.

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When there is no nuclear ring, the inner ring is at this turn-over. But there are some exceptions (NGC 4736, where the turn-over is much inside the ring). This coincidence has to be taken with great caution. Indeed, rings are often associated with non-axisymmetric perturbations (either bars, or tidal interactions), and non-circular velocities are frequent in the ring regions. Then, the accumulation of matter in an elliptical ring could strongly affect the velocity field: the apparent rotation curve could present a maximum just in the ring, without any real maximum of the rotation curve deduced from the axisymmetric potential.

Nuclear rings are often the site of a starburst: this is the case for the well-known NGC4321, 1097, 1433, 3310, 4314 (see list from Hummel et al 1987). Arsenault (1989) found a high preponderance of bars and rings features in starburst galaxies.

As for the molecular distributions, nuclear rings are very rich in CO emission. The most famous examples are M82 (Lo et al 1987), NGC 1068 (Planesas et al, this conference), IC342 (Ishizuki et al 1990), NGC1097 (Gerin et al 1988). More numerous are all the circumnuclear rings not resolved in molecules but hinted at by the kinematical data: double-horn spectra towards the center, where no CO emission at the systemic velocity suggests a ring-distribution.

II-Mechanisms

I will describe the essential mechanisms that have been proposed so far to produce nuclear or inner rings:

- *Viscous torques* (Icke 1979, Silchenko and Lipunov 1987, Lesch et al. 1990)

- *Outflowing winds* thermally driven by the violent SFR: Galactic bipolar flows (Chevalier and Clegg 1985; Sofue 1988; Tomisaka and Ikeuchi 1988)

- *Gravitational torques* and Lindblad resonances (Schwarz 1984, Combes and Gerin 1985)

A- Viscous torques:

Ring formation from viscosity was first developped by Icke (1979): but the theory of viscous torques is well-known from Lynden-Bell and Pringle (1974). They showed that the evolution of any gaseous disk can be characterised by an *expansion* of the outer parts that carry most of angular-momentum, and consequently a *collection* of an ever increasing mass towards the center.

Indeed the theory is based on the fact that for a total angular momentum (AM) given, the least energy of a rotating disk is obtained for a uniform rotation. This is very easy to demonstrate (see Lynden-Bell and Pringle, 1974).

Since Ω decreases with radius in a normal galaxy, the outer parts will gain AM and energy in viscous exchanges (or collisions) to tend to the uniform rotation state of least energy. But the specific angular momentum is a monotonously increasing function of radius. Therefore, AM will be distributed to the regions of the disk that are richer in AM.

Now to remain in equilibrium, the matter that receives AM has to increase its radius. This implies also that its Ω decreases, and the system is going away from the desired uniform rotation state! The process is divergent, and no equilibrium will be reached until all the matter has fallen towards the center.

How does the viscosity acts to make the system evolve this way? The reasoning was until now only based on energetic principles. Viscosity (or equivalently cloud-collisions) produce shearing forces on each gaseous ring, that compose to produce a torque. Shearing forces tend to cancel the relative velocity between two adjacent gaseous rings. Since Ω is decreasing with radius, the torque will tranfer angular momentum to the outer parts. The ideal state, where there would be no viscous forces, is again the uniformly rotating disk. The analysis above tells us however that uniform rotation is unstable in presence of viscosity.

What is the **physical nature of viscosity** in gaseous galactic disks ? In other words, how can energy and AM be transfered at large-scale: large relative velocities are needed for these exchanges. The *molecular* viscosity is of course negligible. But there are large random velocities between interstellar clouds, which are supported by star formation. These motions give rise to the *turbulent* viscosity. To modelise galactic disks, we should know the amount of random motions in function of radius, or location with respect to spiral arms (all quantities not well-known, and even controversial). Also *large-scales instabilities* could fuel small scale random motions: it is the local effective viscosity (Lin and Pringle 1987). Indeed the gas has a tendency to reduce its velocity dispersion by dissipation. When this dispersion Δv falls below the critical value c_r necessary to ensure stability against axisymmetric perturbation (the parameter $Q = \Delta v / c_r$ falls to 1), than instabilities occur in the disk that heats up again the gaseous component. This is a feadback mechanism to maintain large velocity dispersions.

The estimation of the efficiency of viscous torques in galactic disks were attempted by Lynden-Bell and Pringle (1974), who concluded that viscosity had no importance for galactic disks. The estimated time-scale was $\approx 10^9$yrs at 1kpc and $\approx 10^{11}$yrs at 10kpc, but in the center they believed that the effects were cancelled by uniform rotation.

But that is **precisely the way to have rings!** Icke (1979) noticed that if the rotation is sufficiently uniform inside the turn-over radius R_{max}, then the shear is zero inside. Viscous torques external to the radius R_{max} will *accumulate gas in rings*. The ring is short-lived however, since all the gas is bound to go towards the center. But the time-scale of this process is the more lengthened as the rotation curve is uniform inside the turn-over radius.

Simulations of the effect of viscous torques (Icke 1979, Lesch et al 1990) show that the rings formed have no sharp boundaries. Such smooth rings remind us of molecular rings of the Milky Way's type; they are indeed purely gaseous phenomena.

In summary, viscous torques might explain the existence of some of the rings observed. However, the *effective viscosity* is not known. Also, one should keep in mind that the ring is predicted to have a continuously-varying radius (Däther and Biermann 1990). It is impossible to explain the presence of several rings (for instance in typical ringed barred galaxies).

Silchenko and Lipunov (1987) have investigated the contribution of *dynamical friction* of Giant Molecular Clouds (GMC) against the stellar component. Towards the center, the stellar density is so high that the time-scales are significantly lower than the Hubble time, and this phenomenon cloud play a role in driving the gaseous matter towards the center (this gives an upper-limit to the life-time of nuclear rings).

B- Outflowing winds

In starburst galaxies, the rate of supernovae is very high. If most of the energy input is thermalised, Chevalier and Clegg (1985) suggested that this will produce a hot wind, propagating with spherical symmetry. The wind creates a hole in the embedding diffuse gas. The collimation by the surrounding galaxy-disk implies the formation of a nuclear ring or torus (Sofue 1988). This is like a galactic-scale bipolar flow (Tomisaka and Ikeuchi 1988).

This model is attractive in particular for the M82 galaxy. Indeed the hot wind creates shocks when encountering the dense or diffuse clouds of the surrounding medium: emission lines and even X-rays can be explained. This produces a satisfying model for the filaments observed outside the M82 plane (Mc Carthy et al, 1987).

But quantitative estimations have been made by Chevalier and Clegg (1985) only with small scales (radius of the ring 200pc). Could these be scaled to larger rings for more violent starburst? Other mechanisms could be at work in M82, gravitational for instance. A bar has been seen in the near-infrared by Telesco et al (1990, this symposium).

C- Gravitational torques

The transfer of angular momentum can also be provided by gravitational torques. These require non-axisymmetric potentials and their implied tangential forces. The most frequent in galaxies are in cos(2θ)-shape from bars or tidal interactions. But also is required a non-axisymmetric distribution of gas. Indeed for gas in circular orbits or elliptical orbits aligned with the bisymmetric potential, the net torques will cancel out on average.

Now a bisymmetric perturbation in the potential induces a spiral structure in the gaseous component. This spiral is long-lasting with respect to similar structures in the stars, because of the dissipative nature of the gas: collisions modify the orbits of gas clouds, which can then take all orientations between the two orthogonal directions of stellar periodic orbits. Spiral structure winds by 90° between two resonances.

The gravitational torques have a predictable sign between two resonances (Combes 1988). In particular, they are positive outside corotation, and negative inside for a trailing spiral in a bar pattern: the gas accumulates in rings at Lindblad resonances (Schwarz 1984). The inner ring would correspond to an ultra-harmonic resonance, near corotation (UHR), but seems less stable. The outer rings are at OLR, and nuclear rings at ILR. But the time-scale to form these rings are very different: this is due first to shorter dynamical time-scales in the center, but also stronger cos(2θ) perturbations (and then stronger torques) towards the nuclear regions. While outer rings take a Hubble time to settle in, nuclear rings can form in a few 10^8 yrs (Combes and Gerin 1985; Habe et al 1990, this symposium). Besides, nuclear rings are often of elliptical shape.

With a tidal interaction, the cos(2θ) potential is very transient and strong only in the outer parts, unless it is amplified and propagates as a spiral wave towards the center. Frequently, this triggers the formation of a bar (Noguchi 1987; Gerin et al 1990).Very transiently, ring-like features can be triggered during a tidal interactions. Spectacular "ocular-shapes" have been obtained by Elmegreen et al (1990, this symposium).

Simulations

To demonstrate the efficiency of ring formation by gravitational torques, I will present self-consistent 2D simulations with stars and gas. Self-gravity is computed using the FFT method on 256x256 grids (useful space 128x128). The grid cell is then 250pc, and 4 10^4 stellar particles together with 10^4 to 2 10^4 gas clouds are interacting. The hydrodynamics is based on the cloud-cloud collisions model of Combes and Gerin (1985). Clouds have masses between 10^4 and 10^7 M_o. Small clouds grow by collisions until they become GMC, which have a life-time of 4 10^7 yrs. Energy is re-cycled to the medium at the GMC's dispersion. The collision grid is 240x240: the cell corresponds to 130pc. The gas to total mass ratio is 4%.

Figure 1 and 2 displays the same disk evolution when isolated, and when a companion of equal mass passes by in a bound orbit. **In the first case**, a bar appears after 2 10^9 yrs, and reaches its maximum strength at 4 10^9 yrs. In the same time, a spiral structure is generated in the gas (notice that only the gas component presents the spiral structure, and not the stars). A nuclear ring is formed in a very short time-scale during the bar setting, at the ILR of the bar. Gas inside corotation has been cleared up to accumulate in the ring. In the mean time, gas outside corotation is driven outwards, but much more slowly. This is shown in fig 3, where is plotted the evolution of the specific angular momentum. **In the second case,** a bar and a nuclear ring appears in about the same time-scale, but the bar is weakened by the continuous perturbation of the companion. In fact, the tidal interaction dominates the action of the bar outside the bar corotation. There a spiral pattern appears in the gas at each companion passage, and the pattern velocity is that of the companion. The gas, inside the companion CR, but outside the bar CR, is subject to a negative torque and is driven inwards.

Gravitational or viscous torques?

A minimum viscosity is required for the gas to be in a spiral structure, and we could wonder about the importance of this viscosity. First, we ran a test simulation, with the self-gravity suppressed, but the gas hydrodynamics maintained. The radial distribution of the gas remained stationary for a Hubble time. This is possible, since the GMC dispersion (where energy is re-cycled into the gas) acts as a feedback process to compensate for the energy loss in collisions. But of course, since there was no spiral or bar perturbation, the number of collisions was less than for the self-gravitating simulations.

Then we estimated the viscous torques, by computing the net balance between loss and gain of angular momentum in cloud collisions, for a given specific angular momentum. The gravitational torques were also computed from the gravitational forces. The viscous torques appear to be 2 orders of magnitude lower than the gravitational ones. This explains why the gas is driven outwards outside bar corotation in the isolated case, in spite of the presence of viscous torques.

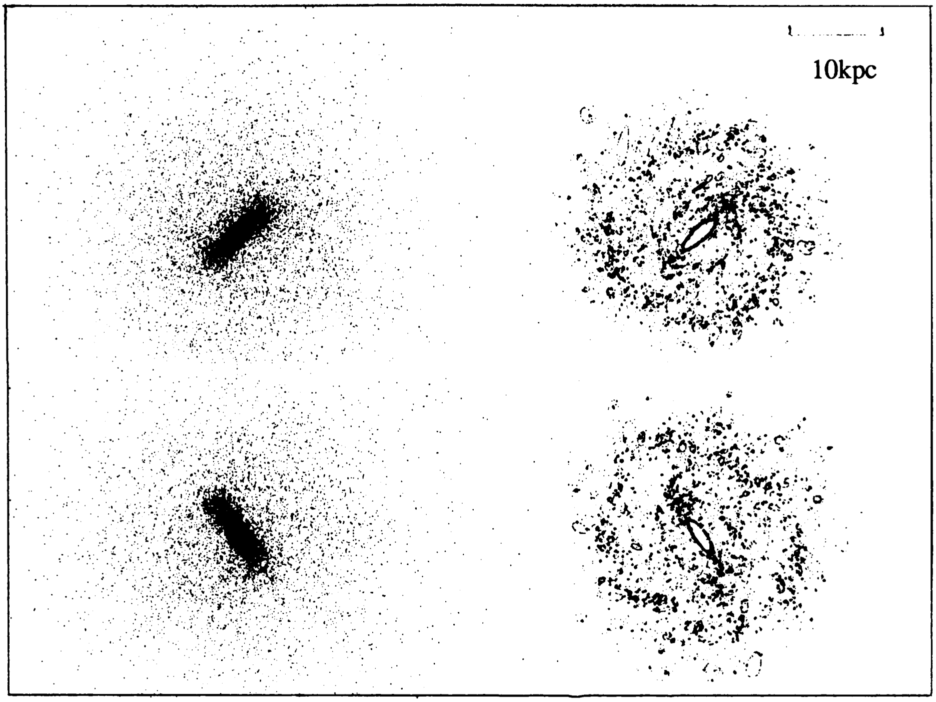

Figure 1: Simulation of an isolated galaxy, with stars initially distributed in a Toomre disk with Q=1, stabilised by a spherical bulge of twice the mass of the disk. A bar yet appears and settles down at 4 10^9 yrs. Left is represented the stellar component, and right the gas particles. These are clouds with a mass and size spectrum, and the small bubles correspond to GMC's dispersion in small clouds with velocity dispersion of 10km/s. The nuclear ring size is about 40 times the resolution of the simulation.

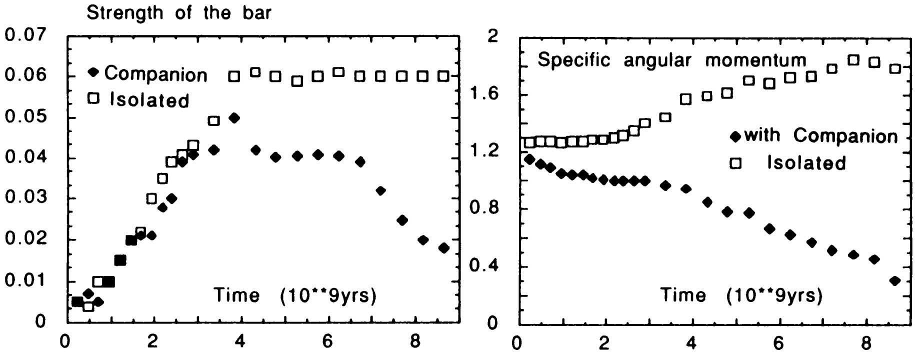

Figure 3: Strength of the bar, and specific angular momentum, corresponding to simulations of fig1 and 2.

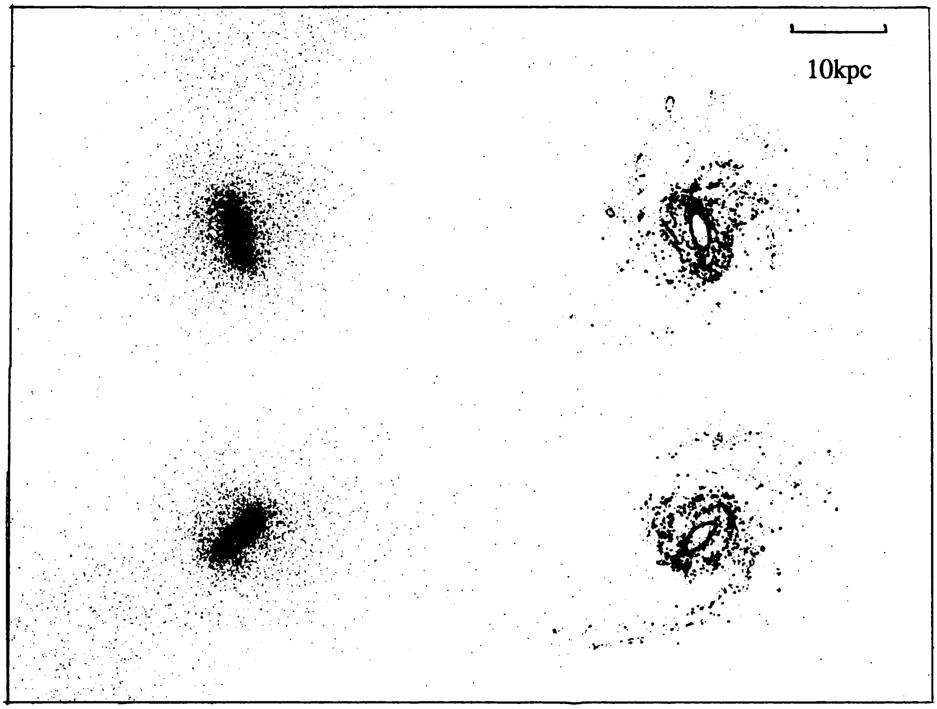

Figure 2: Same as in fig.1, but with a companion in a bound orbit.

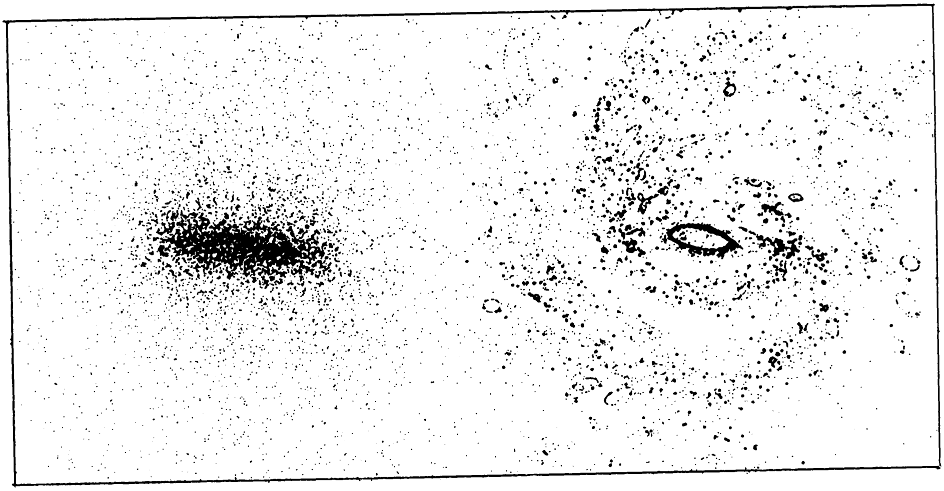

Figure 4: Same as in fig.1, but with a companion in an unbound orbit (scalex2).

III- Conclusions

These self-consistent gas and stars simulations show that viscous torques are negligible with respect to gravitational torques, when a relatively strong bar or tidal interaction is present. Ring formation occurs also in the presence of a weak oval distortion (see the case of NGC4736, Gerin et al this symposium). Gas is accumulated in rings by gravitational torques; nuclear rings form in a much shorter time-scale that outer rings.

When perturbed by a bound companion, the gas component develops a spiral structure in the outer parts, that corotates with it. This prevents the action of the bar of driving this gas outwards, and more gas accumulates in the nuclear ring than in the isolated case. When the galaxy disk is perturbed by an unbound companion, the result is more similar to the isolated case (fig.4).

After 10^{10} yrs, the nuclear ring itself has collapsed towards the center. This could then come either from viscous torques, since in the ring the gravitational torques have no longer any action. This could also come from dynamical friction of giant clouds on the stellar component.

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