THE GROWTH OF BULGES AND CENTRAL MASS CONCENTRATIONS BY DISSIPATIVE PROCESSES

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ABSTRACT. The presence in the central few kpc of a disk galaxy of (1) a bar or a triaxial bulge, (2) a central mass concentration, and (3) a weak dissipation, make up the dynamical ingredients able to speed up considerably, (1) the thickening of the disk by vertical instabilities, and (2) the angular momentum losses, necessary to further accretion of mass. Some consequences compatible with observations are that bulges can be formed in large part *after* the disk formation phase, and that bars can be destroyed by a central mass concentration of about $10^9 M_\odot$.

1. Large Scale Physics of Galaxies

In typical quiet disk galaxies, the energies susceptible to play a dynamical role are to first order the bulk kinetic and gravitational energies ($\approx 200\,\mathrm{eV\,cm^{-3}}$ near the Sun). The other forms of energies, such as the thermal energy of the gas, or the energies stored in magnetic fields or cosmic rays are much smaller ($\approx 1\,\mathrm{eV\,cm^{-3}}$ each), and appear as resulting mainly as by-products of stellar activity and large scale motion. The energy susceptible to be liberated in nuclear reactions by stars, typically 10^{-3} the rest energy of stars ($\rho_\star c^2 \approx 4\times 10^9\,\mathrm{eV\,cm^{-3}}$ near the Sun), is quite large, and is a good candidate to play a dynamical role where star formation does occur. The output of supernovae and WR stars have indeed macroscopical effects over many hundreds of pc, as witnessed by the HI holes, gas bubbles, etc.

Therefore, the description and understanding of galaxies can be taken following successive levels of refinement. We take as paradigm of galactic dynamics the momentum equation of fluids, where D_t is the Lagrangian time derivative,

$$D_t(\rho v) = -\rho\,\nabla\Phi - \nabla P + F_{\mathrm{fric}}(v). \tag{1}$$

The first two terms are usually dominant, just because the corresponding kinetic and gravitational energies are large, which means that motion is, to first order, the one of test particles in the potential Φ. The next two terms, pressure gradients and viscous forces, are perturbations of the first two terms. As stars in galaxies feel

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rather the global gravitational field, rather than the local one (which results in long mean free-paths), self-gravitation is also often a second order effect.

So usual galaxies can be described for a few crossing times by the motion of test particles in a fixed gravitational potential, i.e. by orbits. For longer time-scales, something like 10–20 rotational periods, the hypotheses of pure stellar dynamics seem nowadays no longer to apply very well. Self-gravitation, gas pressure and dissipative terms have to be considered. Self-gravitation introduces mainly long range collective perturbations, since the star distribution in galaxies is smooth over scales of the order of 200 pc, while pressure introduces short range collective constraints, as particles must move coherently in a smooth flow. Whenever a smooth flow is impossible, because the possible orbits are self-intersecting, gas particles have to collide, shocks occur. The viscous terms are responsible of dissipation, without them the system would be conservative.

2. General Effects of Dissipation

A dissipative perturbation of a conservative dynamical system modifies completely its phase space structure. As illustration, Fig. 1 (left) shows a prototype conservative dynamical system, a simple 2D area preserving map, the "standard" map,

$$x_{n+1} = x_n - K\sin(x_n + y_n), \qquad y_{n+1} = x_n + y_n, \qquad \bmod 2\pi. \tag{2}$$

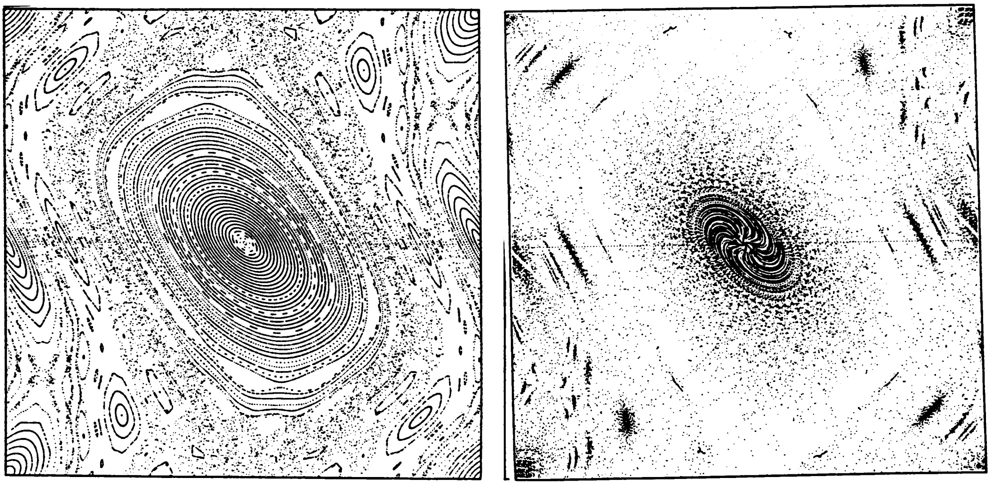

Fig. 1. Standard map with K=1 (left), modified by a weak dissipation (right).

Phase space is made by periodic orbits (e.g. the central fixed point), by quasi-periodic orbits (dots aligned along curves), and chaotic orbits (randomly distributed dots). The effect of a weak dissipative perturbation to Equ. (2) shown in Fig. 1 (right) is to merge the asymptotic states of all the orbits into a few particular

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orbits, called attractors. The introduction of a weak dissipation in conservative systems transforms asymptotically stable periodic orbits into fixed points, some quasi-periodic orbits into limit cycles, and some chaotic orbits into "strange" (chaotic) attractors. When the attractors are known, one can then ask how fast orbits converge towards them, and, for a given dissipation law, which additional factors determine the rate of accretion.

Numerical experiments show that for a weak dissipation, weak meaning that phase space is still strongly influenced by the conservative limit, striking effects occur mainly at the resonances[1]. Everything being equal, the rate of action loss increases strongly when a particle is forced by dissipation to cross a resonance. The presence of resonances or not is the crucial point to consider.

3. Resonances in Singular Axisymmetric Potentials

Galactic potentials are constrained by many factors. In particular, since density is positive, in an axisymmetric potential $\Phi(R,z)$ an inequality between the circular orbit frequency Ω and the radial and vertical epicyclic frequencies κ and ν holds, $\Delta\Phi(R,0) = \kappa^2+\nu^2-2\Omega^2 \geq 0$. Furthermore, stable circular orbits require $\Omega^2>0$, $\kappa^2>0$, and $\nu^2>0$. Galaxies most of the time have convex potentials, density profiles decreasing outwards. All these constraints allow to show that ***horizontal and vertical resonances*** of low order can not be avoided if the density is singular (even mildly) at the center[1]. This condition is sufficient but not necessary; very often non-singular models have also horizontal and vertical resonances. Fig. 2 illustrates how axisymmetric resonances are typically modified by the introduction of a small point mass at the center of a regular potential. If the central density profile is even mildly steep, the lowest order resonances are in general one radial and one vertical ILR for direct orbits, and one radial and one vertical 1/1 resonance for retrograde orbits. Now, if a bar or any non-axisymmetric perturbation widens these resonances, these must have dynamical consequences, as the typical growth rates of these low order resonances are of the order of the crossing time.

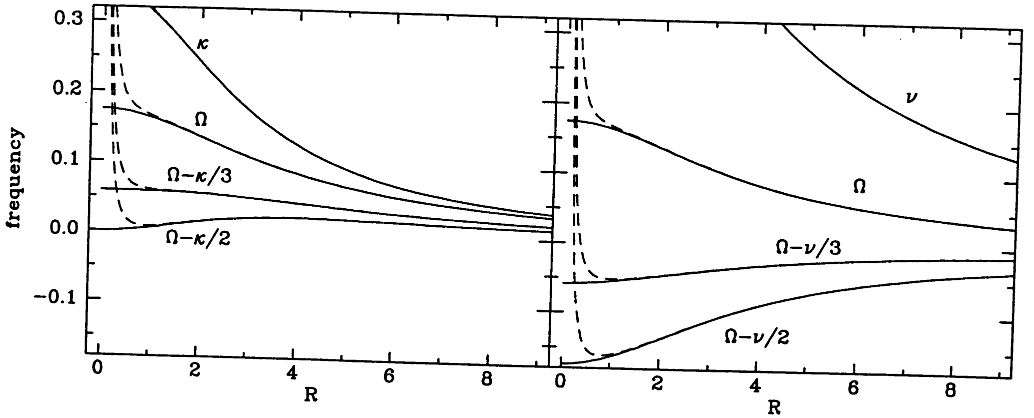

Fig. 2. Low-order radial (left) and vertical (right) resonance diagrams in a Miyamoto potential (solid), and with the addition of a central point mass amounting to 10^{-3} the total mass (dash).

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4. Effects of Bars on Dissipative Particles

So bars in barred galaxies must have strong radial and vertical resonances, especially unavoidable if the density profile is steep near the center. This is indeed very often observed. Since the main attractor in a galactic potential is the center, a singularity can be expected there, which entails ILR resonances.

Any dissipating particle close to a radial resonance loses its radial action ($\sim$ angular momentum) rapidly, the accretion rate is increased. Accretion through an ILR is a self-amplifying process. This reasoning applies as long as particles dissipate. If star formation occurs, a fraction of the initial particles behave subsequently as collisionless particles. For them the effect of vertical resonances can apply, as stars can cross the galactic plane without a noticeable increase of the collision rate. Stars inside a vertical resonance enter the chaotic region, where all integrals of motion dissolve, except the Jacobi integral. The shape of the Jacobi integral inside a rotating bar bounds motion of low energy particles within concentric nearly spheroidal shells[1],[2]. An example of diffusing orbit is shown in Fig. 3. This mechanism can thicken disks and make at least a part of bulges, after the disk formation phase.

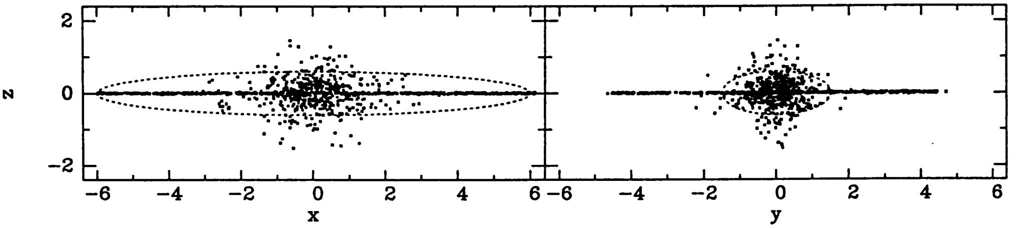

Fig. 3. Edge-on aspect of a dissipating orbit in a barred potential, sampled at regular time-intervals (dots), and starting at the edge of the outlined bar. As the orbit converges towards the center, vertical resonances lift it markedly above the galactic plane into a spheroidal aspect.

5. Effect of Central Mass Concentrations on Bars

Stable periodic orbits within an ILR are known to have an opposite shape to the bar, therefore if the ILR radius is as large as the bar short axis, the bar can no longer be sustained by orbits elongated along the bar[3], the bar has to decrease its eccentricity. N-body models confirm this bar destruction scenario as the central mass concentration grows, as described elsewhere in this volume[4]. A sufficiently large central mass concentration ($\approx 10^9$ $M_\odot$) destroys a bar into a hot, mildly triaxial bulge.

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