22, 23 y 24 de Octubre de 2008. El Escorial (Madrid)

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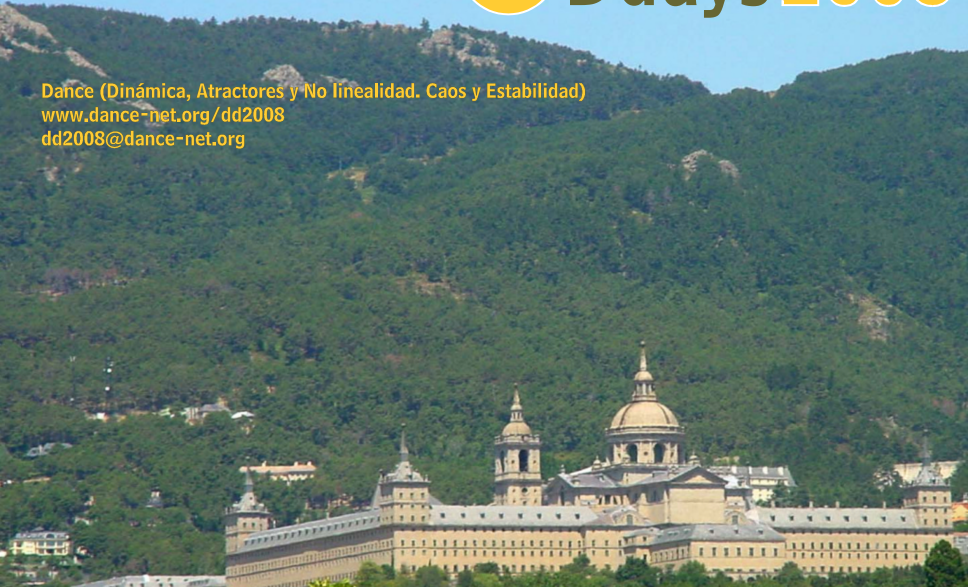


A new theory on the formation of spiral arms and rings in barred galaxies

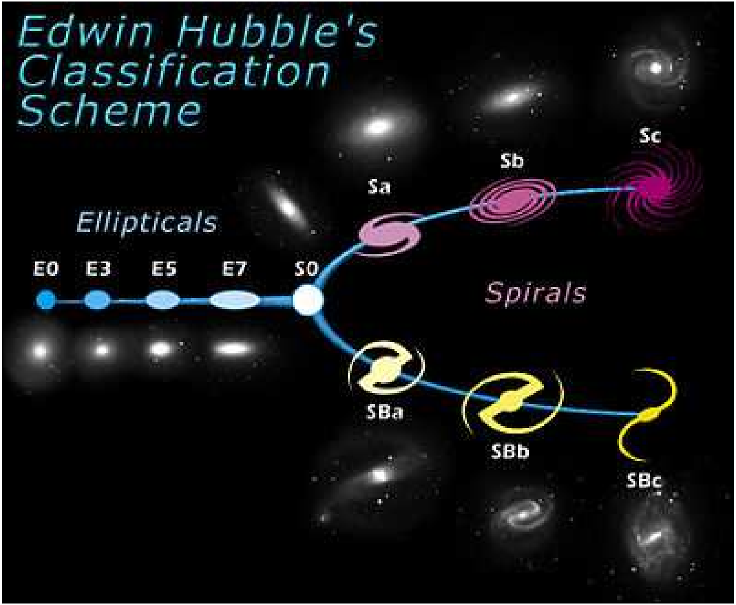
Mercè Romero-Gómez

DDAYS 2008
El Escorial

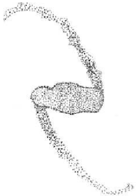
22-24 October 2008

collaborators: J.J. Masdemont, E. Athanassoula

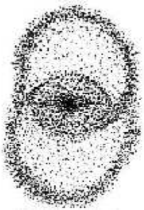
Hubble classification scheme (1925)

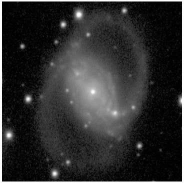


Motivation

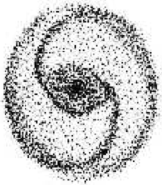


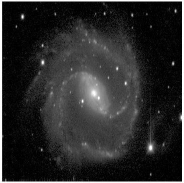
NGC 1365
Spiral arms



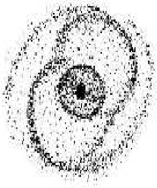


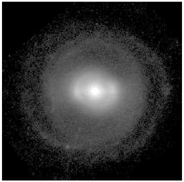
NGC 2665
R_1





NGC 2935
R_2





NGC 1079
R_1R_2

Galactic dynamics

- Families of periodic orbits around the central equilibrium point. Main x_1 family gives structure to the bar: Contopoulos, Athanassoula, Pfenniger, Patsis, Petrou, Skokos, Papayannopoulos in the 80s-90s
- Theories on spiral formation, based on the density waves theory: Kalnajs, Lindblad, Lynden-Bell, Lin, Shu, Toomre in the 70s-80s
- N-body simulations: Kohl, Schwarz, Athanassoula, 70s-80s

Basic characteristics of spiral galaxies - I

- Almost all barred galaxies present two spiral arms.
- Early-type spiral galaxies are brighter and more tightly-wound than late-type.

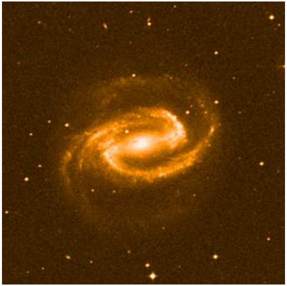


Figure: NGC 1300 - SB(rs)bc

Basic characteristics of spiral galaxies - II

- The rotation curve is typically linearly rising in the central part and flat in the outer region.
- The sense of winding of the arms with respect to the sense of rotation is mainly trailing.

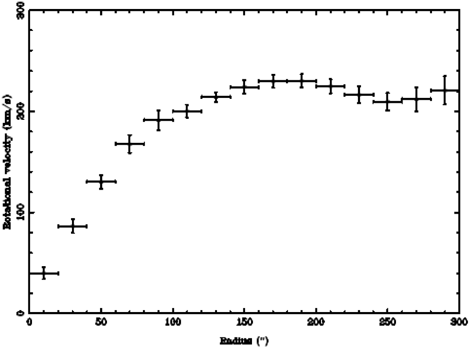


Figure: Rotation curve for NGC 1300; Jörsater, S. and Moorsel, G.A. (1995)

Why studying barred spiral and ringed galaxies? -I

- The origin of spiral structure has been one of the main problems in astrophysics and current theories are kind of "slippery":
  - Swedish astronomer B. Lindblad proposed that spirals result from the gravitational interaction between the orbits of the stars and the disc.
    - Therefore, we have to study them from the stellar dynamics point of view.
    - However, his methods were not appropiate for a quantitative analysis.
  - Lin and Shu proposed that spirals results from a density wave.
    - They can use wave mechanics to explain the properties of the density waves.

Why studying barred spiral and ringed galaxies? -II

- Toomre in the 80s obtains that spirals propagate in the disc from the centre of the galaxy outwards towards one of the principal resonances of the disc, where they damp down:

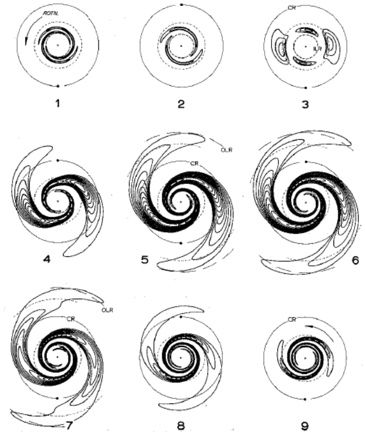


Figure: Toomre (1981)

Obtaining long-lived spirals

Long-lived spirals need replenishment:

- Swing amplification feed-back cycles.
- Driven by a companion.
- Driven by bars.

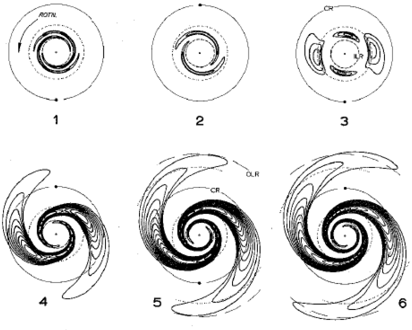
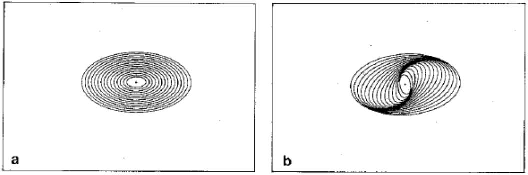


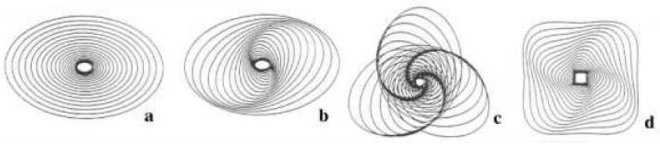
Figure: Toomre (1981)

Other theories related to density waves

- Tidal arms (Toomre & Toomre, 1982): The density waves can be generated via close encounters with companion galaxies. It is a possibility with M51, but it is not accepted as the general theory because there are isolated spiral galaxies, with no companion to interact.
- Magnetohydrodynamic theories: The spiral arms are the result of the interaction of the interstellar magnetic field. However, Spitzer (1978) proofs that the magnetic field is too weak to create density waves.
- Driven by bars or oval distortions: Sanders & Huntley (1976), and other authors later on, studied the relation between bars and spiral arms in barred galaxies. They proposed that shocks in the gas can form the arms, but they do cannot reproduce all types of arms.

Kinematic density waves

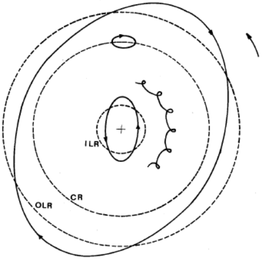




Rings - N-body simulations

Some theories propose that rings are related to the principal resonances of the galaxy:

- ILR related to Nuclear rings
- CR related to Inner rings
- OLR related to Outer rings



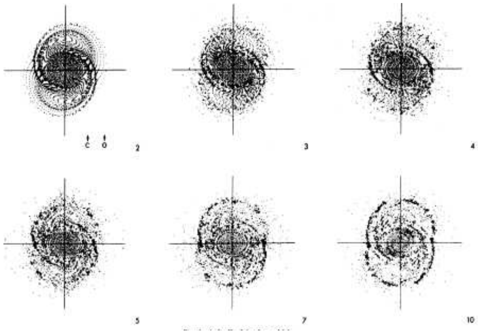
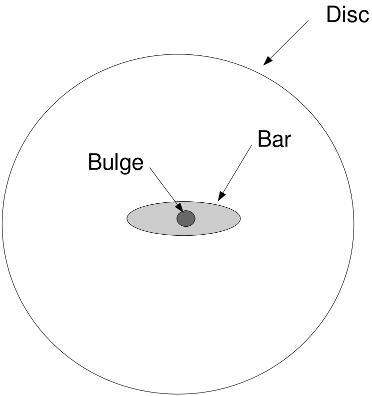


Figure: Schwarz, M.P. (1981)

Example of a test-particle simulation

Components of a barred galaxy



Bar models consist of the superposition of

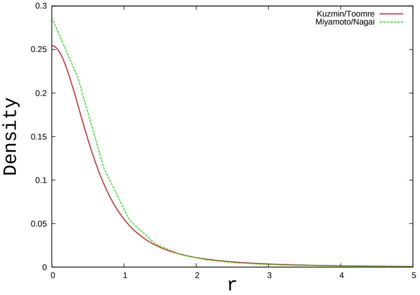
- Axisymmetric component:
  - a disc: Miyamoto-Nagai, Kuzmin/Toomre potentials.
  - a spheroid or bulge: Plummer, spherical potentials.
- and a bar: Ferrers ellipsoids, ad-hoc bar potentials.

The disc

- Discs are flattened, roughly axisymmetric, disc-like structures.
- They have an exponential surface-brightness distribution.
- Represented by Miyamoto-Nagai or Kuzmin/Toomre disc potentials.

$$\Phi_M(R) = -\frac{GM}{\sqrt{R^2 + A^2}}$$

$$\Phi_K(R) = -\frac{3}{2} V_0^2 \left(\frac{3/2}{1/2 + R^2/r_0^2} \right)^{1/2}$$



The spheroid/halo

- They are roughly spherical distributions of stars.
- Represented by a Plummer spheroid or any spheric density distribution.

$$\rho_P(R) = \left(\frac{3M}{4\pi B^3}\right)\left(1 + \frac{R^2}{B^2}\right)^{-5/2}$$

$$\rho(R) = \rho_b \left(1 + \frac{R^2}{r_b^2}\right)^{-3/2}$$

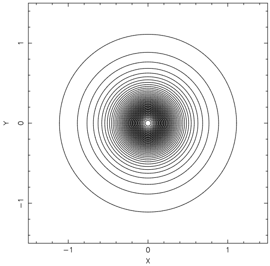


Figure: Isodensity curves for the spheroid.

Bar characteristics

- Bars are non-axisymmetric triaxial features with high ellipticities. The typical axes have length scales proportional to 1:2.
- Bars are not centrally condensed. The surface brightness is
  - nearly constant along the semi-major axis.
  - steep and falls off sharply along the semi-minor axis.
- Bars extend up to CR. The ratio $R_{CR}/a = 1.2 \pm 0.2$ and rotate fast.

Bar component

- Ferrer's ellipsoid: $\rho = \begin{cases} \rho_0(1-m^2)^n & m \leq 1 \\ 0 & m \geq 1, \end{cases}$
- Dehnen's bar type:

$$\Phi(r,\theta) = -\frac{1}{2}\epsilon v_0^2 \cos(2\theta) \begin{cases} 2 - \left(\frac{r}{a}\right)^n & , \quad r \leq a \\ \left(\frac{a}{r}\right)^n & , \quad r \geq a \end{cases}$$

- Barbanis-Woltjer's type: $\Phi(r,\theta) = \hat{\epsilon}\sqrt{r}(r_1 - r)\cos(2\theta)$
- Bar+spiral: density:

$$S(r,\theta) = A(r) \begin{cases} \cos(2\theta) & , \quad r \leq a \\ \cos(2\theta - \phi(r)) & , \quad r \geq a \end{cases}$$

Equations of motion

- The equations of motion of a rotating system are described in vectorial form by:

$$\ddot{\mathbf{r}} = -\nabla\mathbf{\Phi}_{\mathrm{eff}} - 2(\mathbf{\Omega} \times \dot{\mathbf{r}}),$$

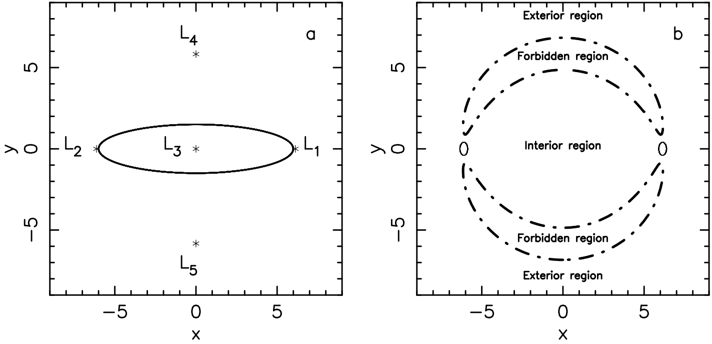
where $\mathbf{r} = (x, y, z)$ is the position vector and $\mathbf{\Omega} = (0, 0, \Omega)$ is the rotation velocity vector around the z-axis, and $\Phi_{\mathrm{eff}} = \Phi - \frac{1}{2}\Omega^2\left(x^2 + y^2\right)$ is the effective potential.
- We define the Jacobi constant or Jacobi energy as $E_J = \frac{1}{2}|\dot{\mathbf{r}}|^2 + \Phi_{\mathrm{eff}}$.
- The zero velocity surface of a given energy level is the surface obtaine when: $\Phi_{\mathrm{eff}}(x, y, z) = E_J$. We define the zero velocity curve, its cut with the $z = 0$ plane.

Equilibrium points

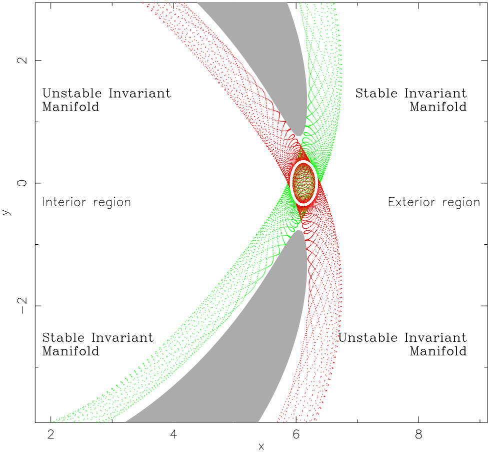
- The equilibrium points of the system are located where

$$\frac{\partial \Phi_{\mathrm{eff}}}{\partial x} = \frac{\partial \Phi_{\mathrm{eff}}}{\partial y} = \frac{\partial \Phi_{\mathrm{eff}}}{\partial z} = 0.$$

They lie on the xy-plane: L_1 and L_2 along the bar major axis, L_3 on the origin, and L_4 and L_5 along the bar minor axis.



Nonlinear stable and unstable invariant manifolds

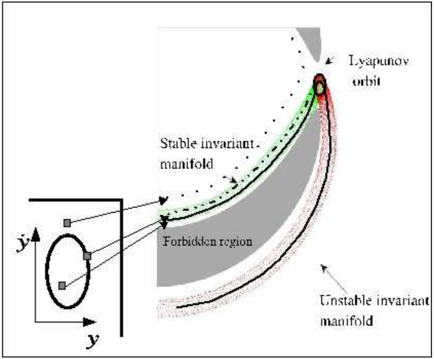


Romero-Gómez et al. (2006)

Transit orbits

Transfer of matter from the interior to the exterior region:

- Transit orbits have initial conditions *inside* the $W^{s,1}_{\gamma_i}$ curve in the $y\dot{y}$ plane.
- Non-transit orbits have initial conditions *outside* the $W^{s,1}_{\gamma_i}$ curve in the $y\dot{y}$ plane.

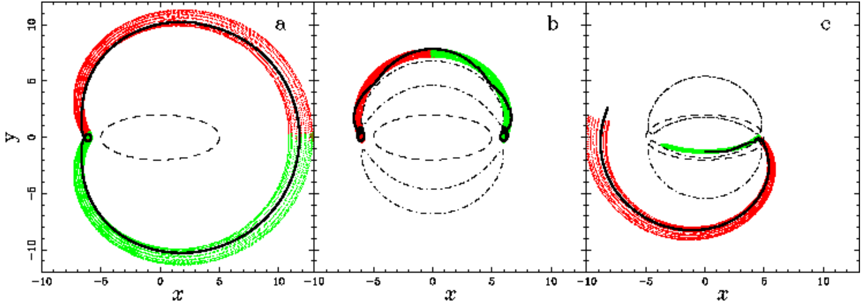


Show transit and non-transit movie

Transfer of matter: Homoclinic and heteroclinic orbits

- Homoclinic orbits, ψ, s.t. $\psi \in W^u_{\gamma_i} \cap W^s_{\gamma_i}$, $i = 1, 2$
- Heteroclinic orbits, ψ', s.t. $\psi' \in W^u_{\gamma_i} \cap W^s_{\gamma_j}$, $i \neq j$, $i, j = 1, 2$

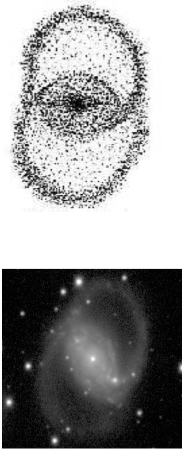
Romero-Gómez et al. (2007)



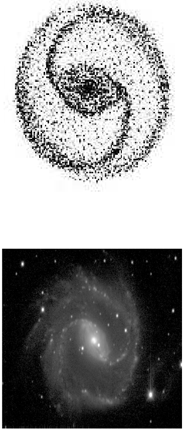
Homoclinic Heteroclinic Transit

Motivation

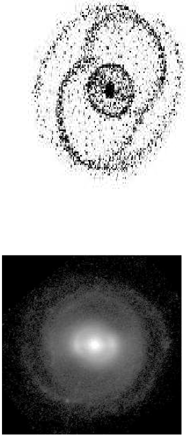
NGC 1365
Spiral arms



NGC 2665
R_1



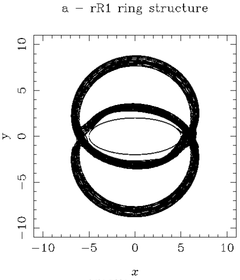
NGC 2935
R_2

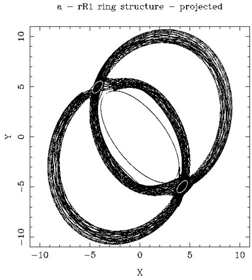


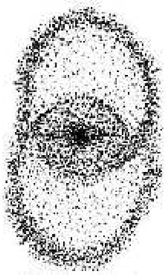
NGC 1079
R_1R_2

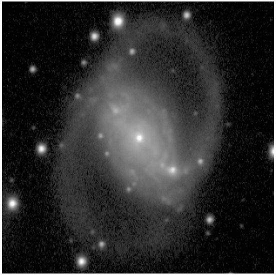
R_1 rings

- If there exist heteroclinic orbits, the morphology obtained is **r$\mathbf{R_1}$ ring** structure.



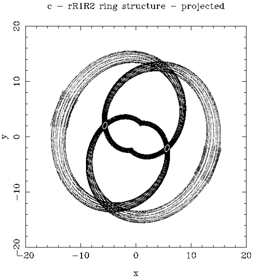


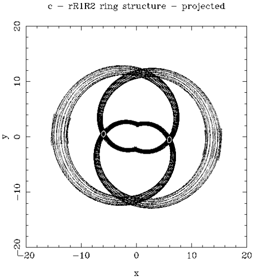


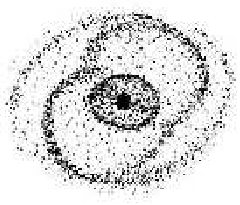


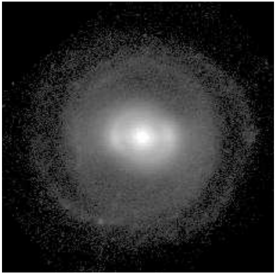
$R_1 R_2$ rings

- If there exist homoclinic orbits, the morphology obtained is **$\mathbf{rR_1R_2}$ ring** structure.



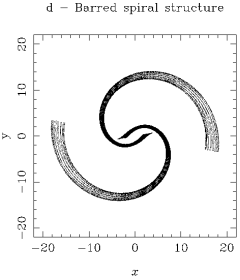


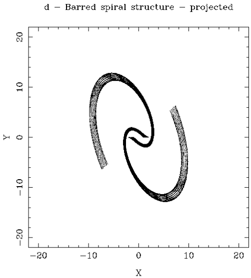


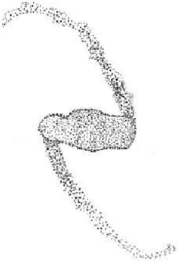


Spiral arms

- If there are no heteroclinic or homoclinic orbits, the morphology obtained is two **spiral arms**.

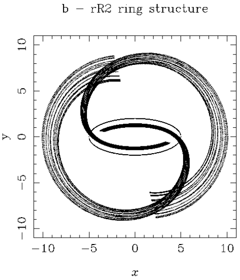


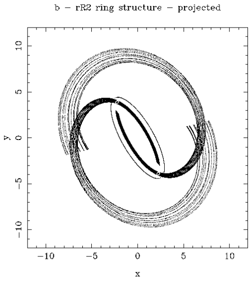


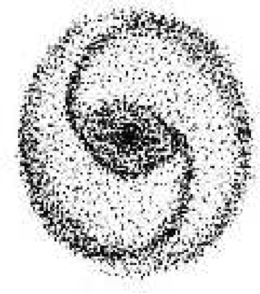


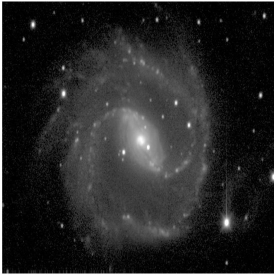
R_2 rings

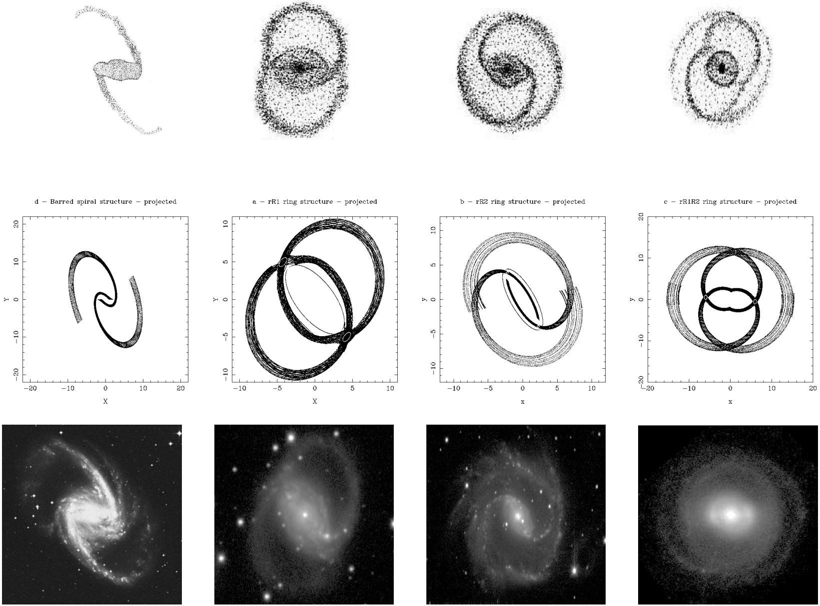
- When the pitch angle is adequate, the spiral arms cross each other and form **$\mathbf{R_2}$ rings**.







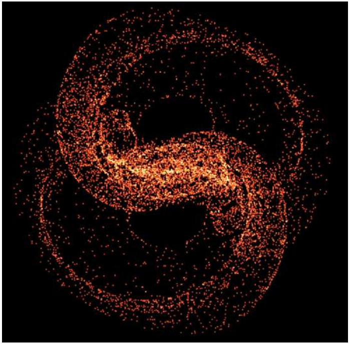


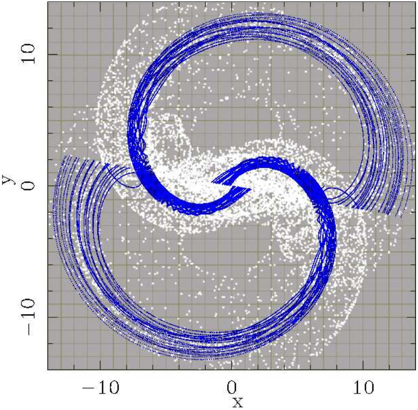


NGC 1365	NGC 2665	NGC 2935	NGC 1079
Spiral arms	R_1	R_2	R_1R_2

Simulation - response. Where does all the material on these orbits comes from? Only from the immediate neighbourhood of the Lagrangian points?

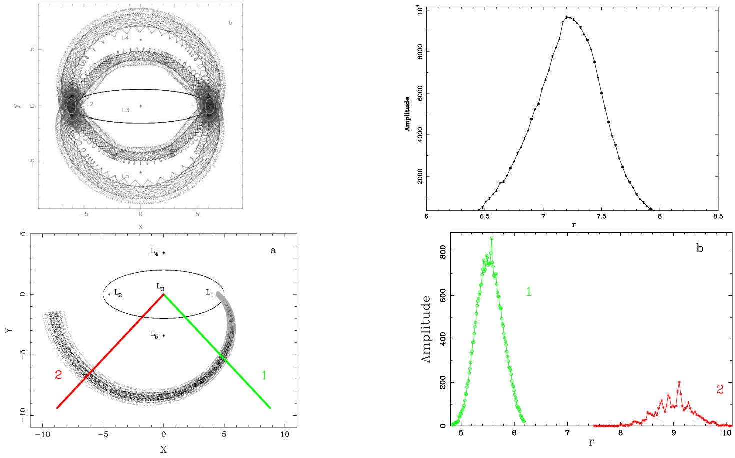
Not necessarily. In fact, most of it can come from the outer parts of the bar, driven to the L_1/L_2 and to the unstable manifold by the inner branch of the stable manifold.



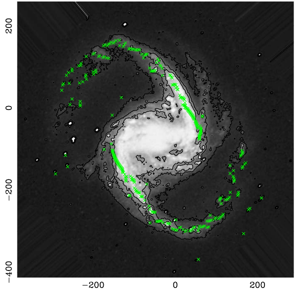


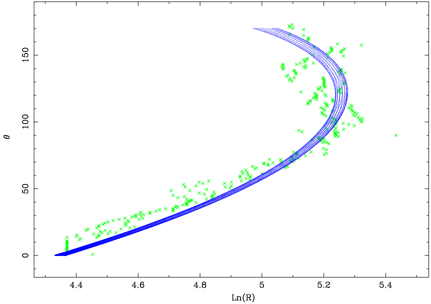
Photometrics: Radial profile

The density profile along a cut across the ring and spiral arms has the same properties as in observations.
Romero-Gómez et al. (2006)



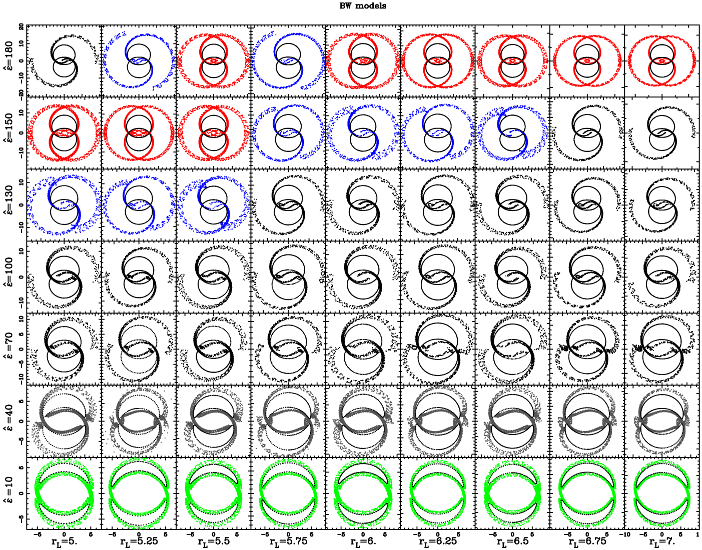
Photometrics: Pitch angle





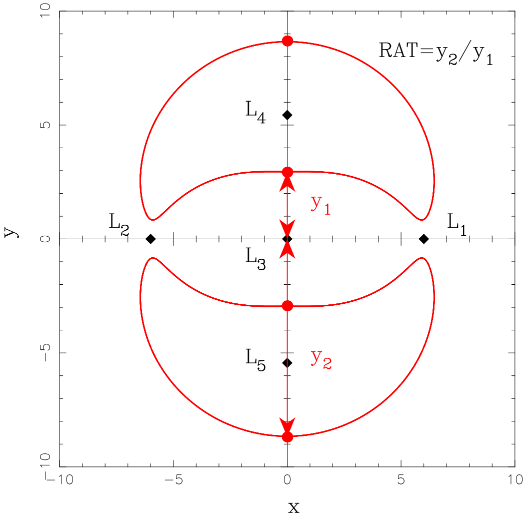
2D parameter study - BW type of bar

Athanassoula, Romero-Gómez & Masdemont (in preparation)



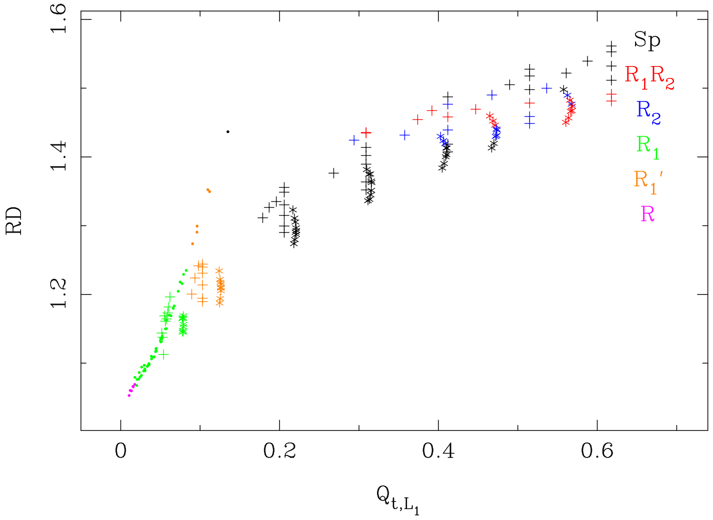
Is there a quantity, valid for all barred galaxy potentials, that can predict whether a model/galaxy will be spiral, R_1, R_2 or R_1R_2 ? Yes (?)

- $q_r = \dfrac{\partial\Phi_2/\partial r}{\partial\Phi_0/\partial r}$
- $q_t = \dfrac{(\partial\Phi/\partial\theta)_{max}}{r\partial\Phi_0/\partial r}$
- $\Phi_{\rm eff} = \Phi - \frac{1}{2}\Omega_p^2\,(x^2+y^2)$
- $\mathrm{RAT} = \dfrac{y_2}{y_1}$



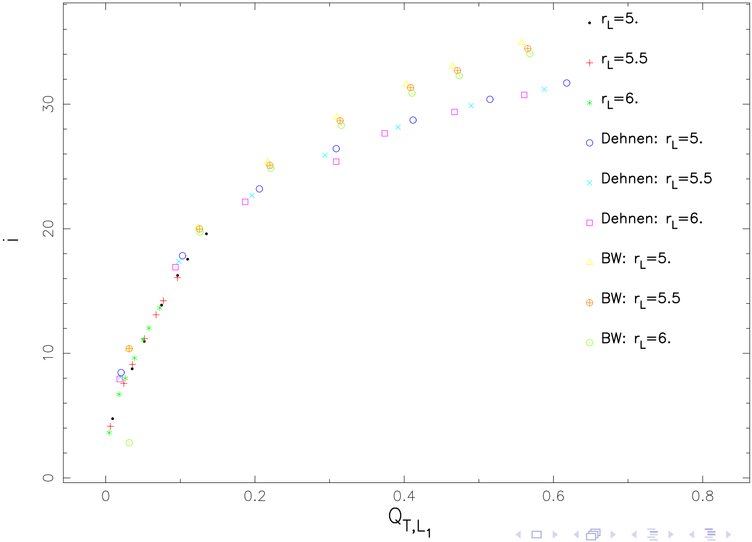
2D parameter study - prediction tool

Athanassoula, Romero-Gómez & Masdemont (in preparation)



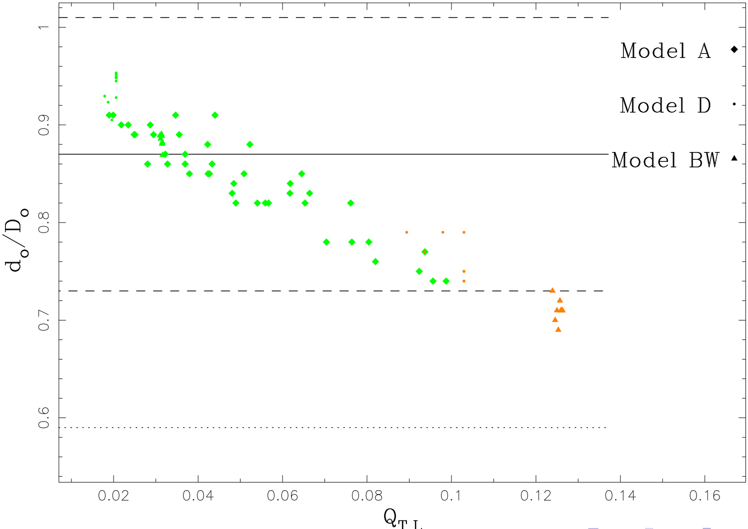
Pitch angle vs strength parameter

According to observations, the pitch angle of the spiral arm increases in galaxies with a strong bar.



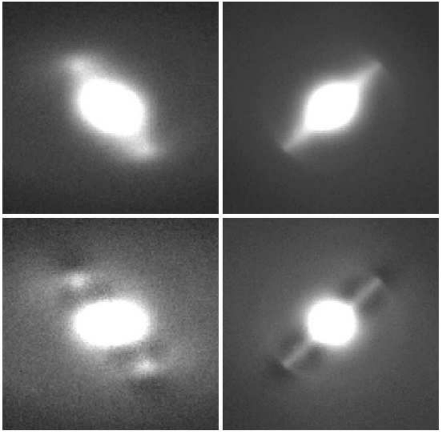
Ratio of the outer ring diameters vs strength parameter

We find a good correlation between the ratio of the outer ring diameters with the strength of the bar.



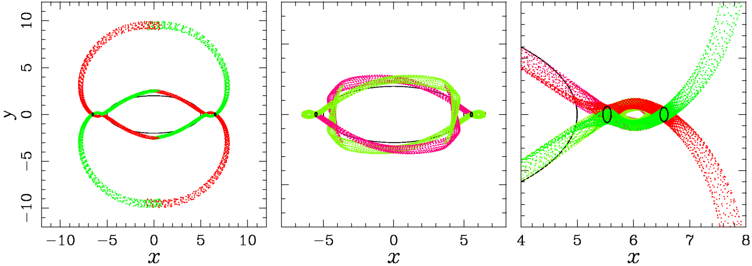
Stabilisation of L_1 and L_2 - ansae formation? -I

What if material gets concentrated at the ends of the bar?



ansae bars "normal" bars

Stabilisation of L_1 and L_2 - ansae formation? -II



Summary

- Here we propose a new theory on the formation of spiral arms and rings in barred galaxy, form the dynamical systems point of view.
- We studied the dynamics of the L_1 and L_2 unstable Lagrangian points, of the Lyapounov orbits and of the invariant manifolds.
- The manifolds:
  - They extend far from the unstable Lagrangian points L_1 and L_2 and thus can drive global structures
  - They have the right shapes and reproduce all known types of spiral and ring shapes (R_1, R_2, R_1R_2)
  - Their photometric radial profiles are in global agreement with observations (Schweizer 1976)
  - The loci they outline agrees well with the high density regions in simulations
- The unstable and stable invariant manifolds could be the building blocks for spiral and rings in barred galaxies.