Kinematics of the Milky Way spiral arms driven by the invariant manifolds

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Abstract

Here we present the analysis and properties of the Milky Way stellar arms. We apply the recent theory of the invariant manifolds to obtain the locus of the spiral arms and rings of a bar galactic potential. This theory is based on the dynamics driven by the invariant manifolds of unstable periodic orbits. The invariant manifolds are asymptotic orbits that act as a tube that can trap and drive material (Romero-Gomez et al 2006,2007; Athanassoula, Romero-Gomez & Masdemont 2009; Athanassoula et al 2010). We compute the invariant manifolds of a barred potential, where no spiral perturbation is induced.
We briefly explain the details of the dynamics driven by the manifolds and we compare the properties and locus obtained by the potentials used in the literature to describe the Galactic bar.
In particular, we compare the kinematics given by both the manifolds and the CO emission from observations (Dame, Hartmann & Thaddeus, 2001). To do so we plot longitude - heliocentric radial velocity diagrams, (l,v)-diagrams. We observe that the kinematics driven by the orbits reproduce well the Galactic Molecular Ring and, in some cases, the 3-kpc arms.

Bar potentials and bar strength

Analytic bar potentials, Φ_b

- Ferrers (MR09, GF10)
- Prolate bar (PMM04)
- Quadrupole bar (Dehnen00, Fux01)

The potential and the equilibrium points

- The potential: $\Phi = \Phi_0 + \Phi_b$, where Φ_0 is the axisymmetric component.
- The effective potential: $\Phi_{eff} = \Phi - \frac{1}{2}\Omega_b^2(x^2+y^2)$
- The equilibrium points: $\frac{\partial \Phi eff}{\partial x} = \frac{\partial \Phi eff}{\partial y} = 0$.
- L_1, L_2 saddle points, L_3, L_4 and L_5 stable points.

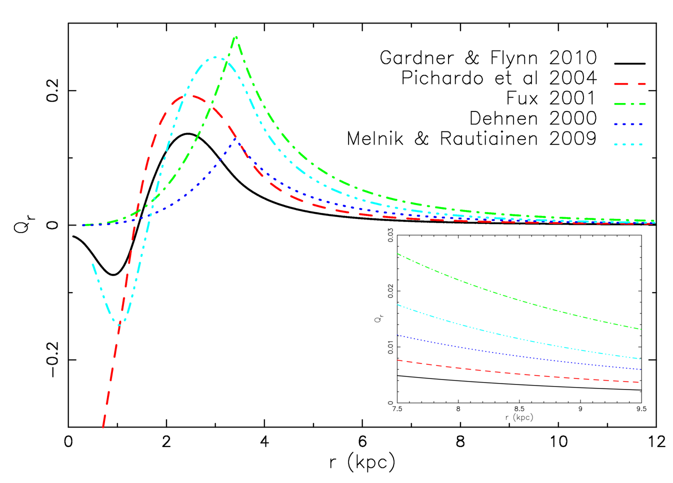
(R,θ) are the cylindrical galactocentric coordinates. R_0 and V_0 are galactocentric the position and circular velocity of the Sun respectively, and r_{L_1} is the distance form the Galactic Centre to L_1.

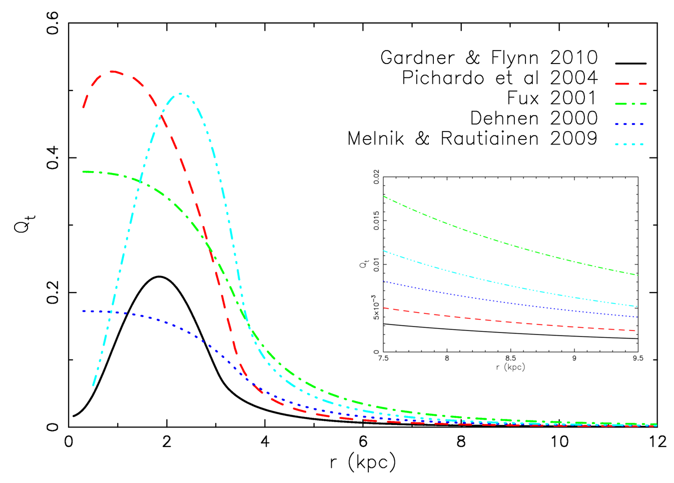
Measuring the bar strength

- Tangential force: $Q_t(R) = \frac{\frac{\partial \Phi(R,\theta)}{\partial \theta}|_{max}}{R\,\frac{\partial \Phi_0}{\partial R}}$
  - $Q_{t,L_1} = Q_t(r_{L_1})$
  - $Q_b = \max Q_t$
- Radial force: $Q_r(R,\theta) = \frac{\frac{\partial \Phi_b(r,\theta)}{\partial r}}{\frac{\partial \Phi_0}{\partial r}}$
  - $\alpha = Q_r(R_0, 0)$

The bar strength in different potentials

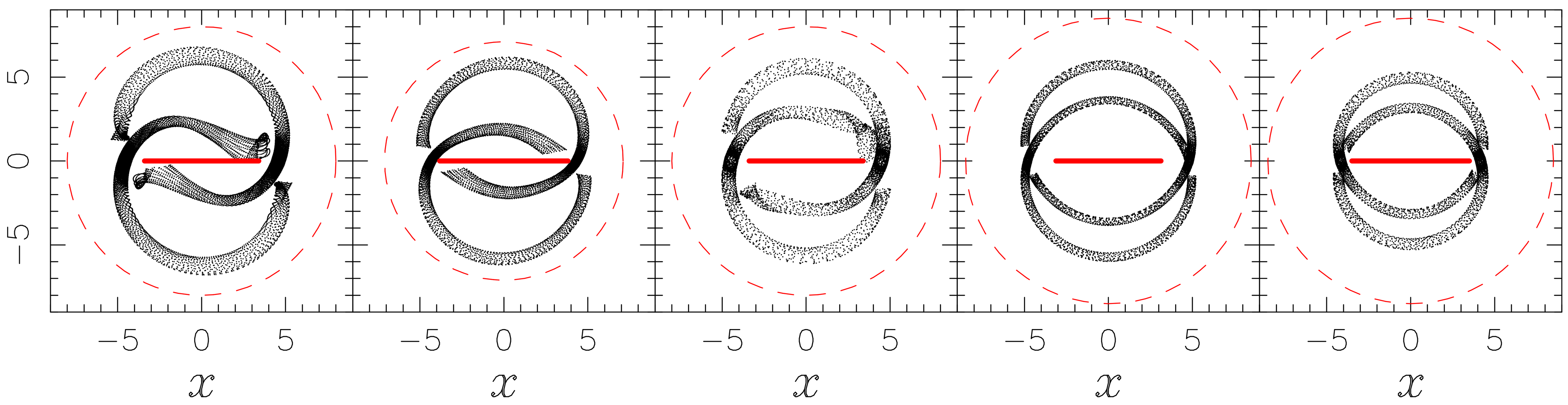
Model	$R_0\,(kpc)$	$V_0\,(km\,s^{-1})$	$r_{L_1}\,(kpc)$	α	Q_b	Q_{t,L_1}
GF10	8.5	239.	4.08	0.0037	0.22	0.023
PMM04	8.5	220.	4.4	0.0051	0.31	0.017
Fux01	8.	200.	4.26	0.022	0.38	0.08
Dehnen00	8.	200.	4.26	0.01	0.17	0.026





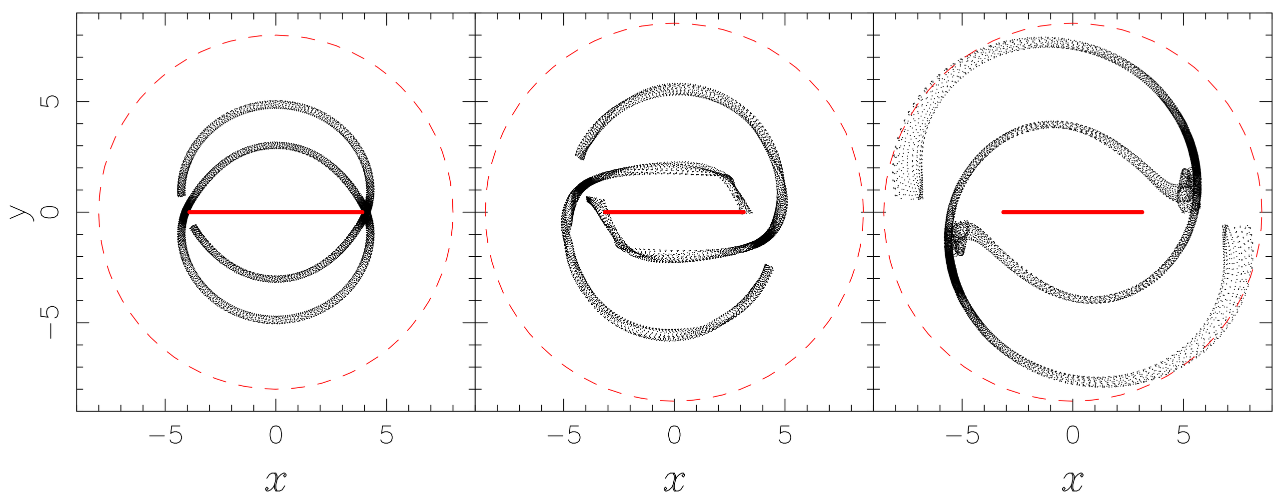
Rings and spirals generated by the Galactic bar

The 5 selected models



Fux01 MR09 Dehnen00 PMM04 GF10

The 3 special cases



GF10 with the Long bar PMM04: Galactic+Long bar PMM04+Spiral PERLAS

Outer and inner ring axial ratios:

Model	Fux01	MR09	Deh00	PMM04	GF10	LongBar	2bars	bar+sp
d_o/D_o	0.74	0.75	0.8	0.88	0.86	0.85	0.82	0.8
d_i/D_i	0.43	0.46	0.66	0.75	0.77	0.74	0.55	0.7

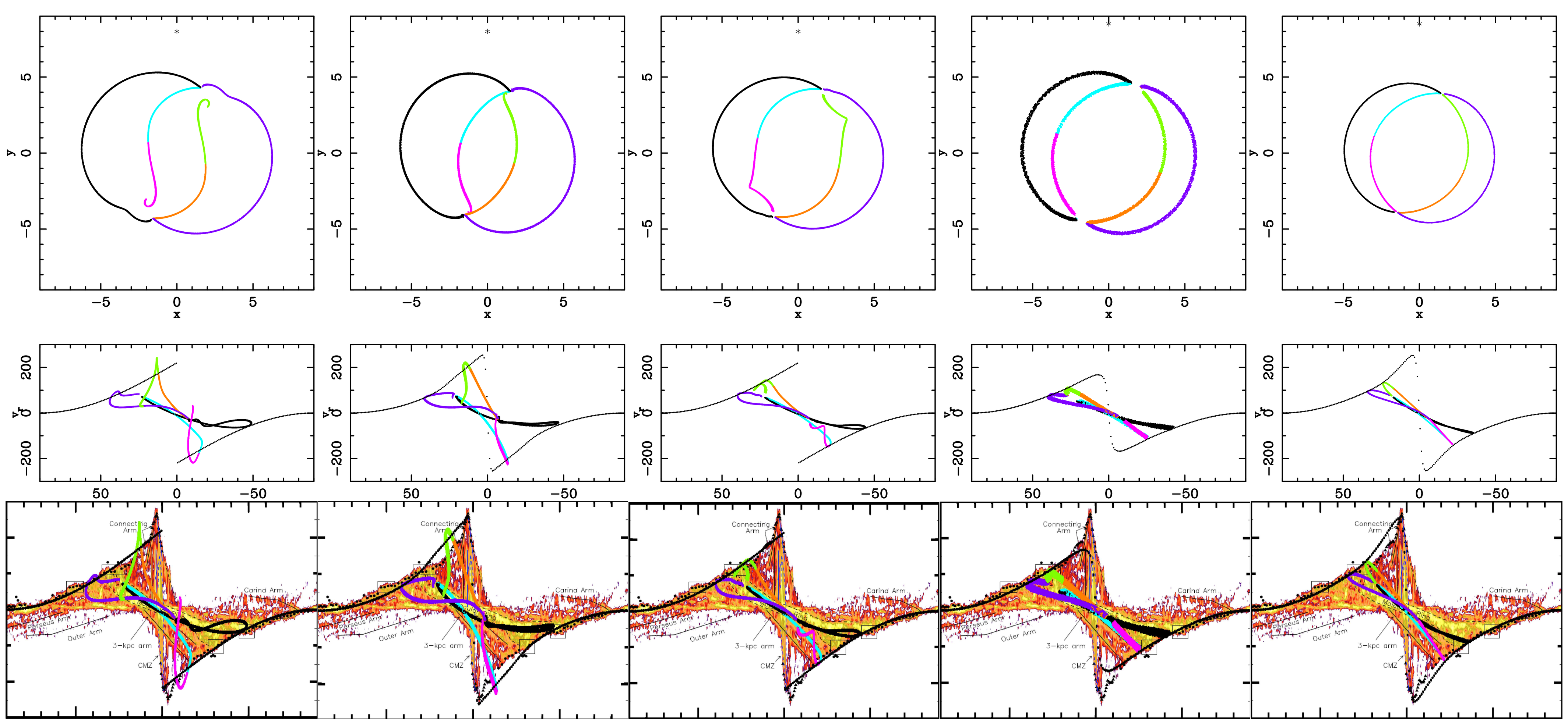
where d_o/D_o denotes the axial ratio of the outer ring, while d_i/D_i denotes the axial ratio of the inner ring.

- All models have a flat rotation curve.
- The red horizontal solid line marks the scale-length of the bar. The dash red circle marks the position of the solar radius.
- Almost in all cases, the large-scale structure is that of rR_1 or rR_1' rings.
  - The outer rings have the size and eccentricity of the Galactic Molecular Ring.
  - In some cases, the inner rings delineate the locus of the near and far 3-kpc arms.
- Only when we impose a spiral perturbation, a tightly-would spiral is obtained.

Kinematics: longitude - heliocentric line-of-sight velocity: comparison between the (l,v) diagram obtained from the orbits given by the model and the one from observations (CO emission, Dame, Hartmann & Thaddeus (2001); Rodiguez-Fernandez & Combes (2008))

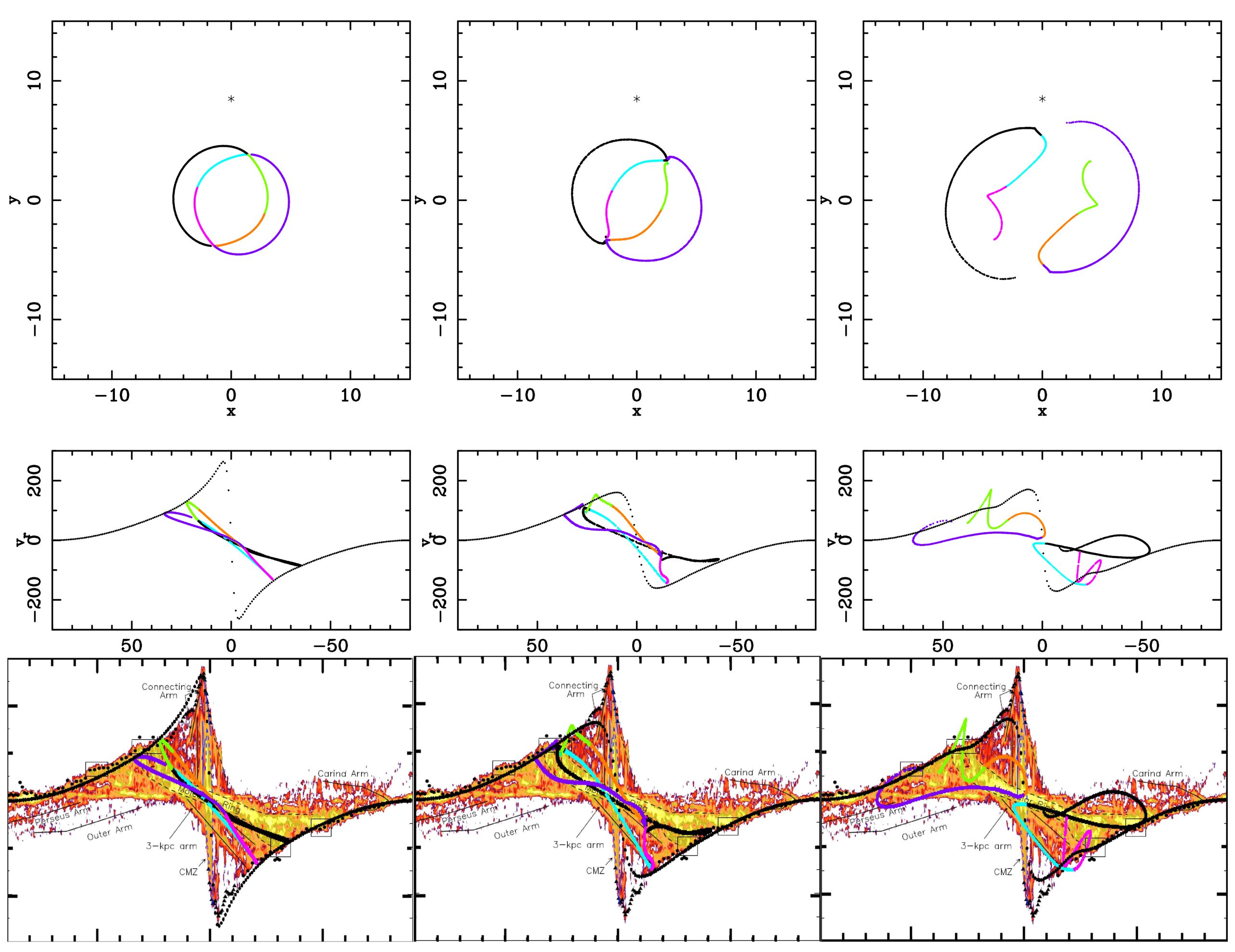
- First row:
  - The asterisk marks the position of the Sun.
  - Here we plot the orbits driven by the manifold of the lowest energy possible. The orbits are rotated 70° in order to have the Sun on the y-positive axis.
- Second row: (l,v)-diagram corresponding to the orbits and colour-code of the first row.
- Third row: Superposition of the plot given on the second row with the (l,v) plot obtained from CO emission (Dame, Hartmann & Thaddeus (2001); Rodirguez-Fernandez & Combes (2008))

(l,v)-diagram of the 5 selected potential models



Fux01 MR09 Dehnen00 PMM04 GF10

(l,v)-diagram of the 3 interesting cases



GF10 with the Long bar PMM04: Galactic+Long bar PMM04+Spiral PERLAS

Conclusions

- **The model is able to reproduce the observed kinematics of the gas of the inner parts of the Milky Way Galactic disc.**
  - The outer ring reproduces well the overdensity in the (l,v)-diagram corresponding to the Galactic Molecular Ring.
  - In some cases (MR09), the size and elongation of the inner ring reproduces the near and far 3-kpc arm.
  - We have checked that more realistic models with 2 bars or bar+spiral also reproduce well the near 3-kpc arm.

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