Vertical Heating of the Stellar disk driven by the Spiral Arms

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Introduction

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The first mechanism invoked to explain the existence of the thick disk in the Milky Way Galaxy, were the spiral arms. There are several other possibilities that together seem to better explain this component of our galaxy, but is not straightforward to quantify the contribution of each one.

We present a study of the effect of spiral arms in the formation of thick disks, as going from early to late type disk galaxies. We perform test particle simulations in a 3D spiral galaxy potential. By varying the parameters of the arms we found that the vertical heating of the stellar disk is very important in some cases, and strongly depends on the galaxy morphology, pitch angle, arms mass and its pattern speed.

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For the arms we use a bisymmetric self-gravitating potential model (Pichardo et al. 2003), which consists of individual inhomogeneous oblate spheroids superposed along a logarithmic spiral locus (Roberts et al. 1979). This is a more realistic potential since it is based on a density distribution and considers the force exerted by the whole spiral structure, obtaining a more detailed shape for the gravitational potential, unlike a 2-D local arm such as the tight winding approximation (TWA).

Table: Parameters of the Galactic Models (Pérez-Villegas et al. 2013)

Parameter		Value Sa	 Sb	 Sc	Reference
Axisymmetric Components					
M_B / M_D		0.9	0.4	0.2	1,2
M_D / M_H		0.07	0.09	0.1	2,3
Rot. Curve ($\mathrm{km\ s^{-1}}$)		320	250	170	4
M_D ($10^{10} M_\odot$)		12.8	12.14	5.10	3
M_B ($10^{10} M_\odot$)		11.6	4.45	1.02	M_B/M_D based
M_H ($10^{12} M_\odot$)		1.64	1.25	0.48	M_D/M_H based
Scale-lengths of the Axisymmetric Components (kpc)					
Bulge:	b_1	2.5	1.7	1.0	
Disk:	a_2	7.0	5.0	5.3178	
	b_2	1.5	1.0	0.25	
Halo:	a_3	18.0	16.0	12.0	
Spiral Arms					
locus		Logarithmic			5,9,10
arms number		2			6
pitch angle (°)		8-40	9-45	10-60	4,7
M_{sp}/M_D		1-5%			9
scale-length (kpc)		7	5	3	disk based
Ω_{sp} ($\mathrm{km\ s^{-1}\ kpc^{-1}}$)		-30	-25	-20	5,8
ILR position (kpc)		3.0	2.29	2.03	
CR position (kpc))		10.6	11.14	8.63	
inner limit (kpc)		3.0	2.29	2.03	∼ILR position based
outer limit (kpc)		10.6	11.14	8.63	∼CR position based

[1] Weinzirl et al. (2009). [2] Block et al. (2002). [3] Pizagno et al. (2005). 4 Ma et al. (2000). [5] Grosbøl & Patsis (1998). [6] Elmegreen & Elmegreen 2014. [7] Kennicutt (1981). [8] Gerhard 2011. [9] Pichardo et al. (2003). [10] Seigar et al. (2006).

Initial conditions

The initial set-up consists in distributing the particles according to the density profile of Miyamoto & Nagai (1975). In this manner, the initial condition for the stellar disk is given by

$$\rho_{MN} = \frac{b_2^2 M_d}{4\pi} \frac{a_2 R^2 + (a_2 + 3\sqrt{z^2 + b_2^2})(a_2 + \sqrt{z^2 + b_2^2})^2}{(R^2 + (a_2 + \sqrt{z^2 + b_2^2})^2)^{5/2}(z^2 + b_2^2)^{3/2}}. \tag{1}$$

where M_d is the mass of the galaxy disk, a_2 and b_2 are the radial and vertical scale-length, respectively. This parameters span a range of values in our simulations in order to capture different galaxy morphologies and kinds of spiral arms.

To assign velocities to the particles, once the density profile has been established, it is necessary to obtain the rotation curve.

$$\Omega_c(R) = \left(\frac{1}{R}\partial_R \Phi\right)^{1/2} \tag{2}$$

and $v_c = R\Omega_c(R)$, so the circular velocity is given by

$$v_c(R) = (R\partial_R \Phi)^{1/2}. \tag{3}$$

When Ω_c is known at any radii we can obtain

$$K = \left(4\Omega_c^2 + R\frac{d\Omega_c^2}{dR}\right)^{1/2} \tag{4}$$

known as the epicyclic frequency, necessary to obtain the velocity dispersion in R and to correct for the asymmetric drift.

To build a stable stellar disk we introduce a dispersion in velocity in the three polar coordinates:

$$\sigma_R = 3.358 \frac{\Sigma(R) Q}{K} \tag{5}$$

$$\sigma_\phi = \frac{1}{2} \frac{\sigma_R K}{\Omega_c} \tag{6}$$

$$\sigma_z = \sqrt{\pi G \Sigma b_2} \tag{7}$$

where K is the epicyclic frequency, $\Sigma(R)$ the surface density, Q is the known Toomre parameter and b_2 is the vertical scale-lenght of the disk.

The asymmetric drift correction is

$$\left\langle v_\phi \right\rangle^2 = v_c^2 - \sigma_\phi^2 - \sigma_R^2 \left(-1 - 2 \frac{R}{\Sigma} \partial_R \Sigma \right) . \tag{8}$$

This is the correction that has to be done due to the fact that stellar orbits are not real circular orbits, instead, orbits follow epicycles around the guide point of a circular orbit and these epicycles are characterized by the epicyclic frequency K.

Finally the particles are distributed in the velocity space as

$$\begin{aligned} v_\phi &= \left\langle v_\phi \right\rangle \pm x\sigma_\phi \\ v_R &= \langle v_R \rangle \pm x\sigma_R \\ v_z &= \langle v_z \rangle \pm x\sigma_z \end{aligned} \tag{9}$$

where x is a random number between 0 and 1, $\left\langle v_\phi \right\rangle$ is given by Eq. (8) and the average radial and vertical velocities are taken as $\langle v_R \rangle = \langle v_z \rangle = 0$.

Measuring the vertical Heating

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The analysis of the effects of the spiral arms over the stellar disk is based in the study of the vertical velocity dispersion and its dependence with the parameters that characterise the spiral pattern.

For each one of the simulations we measure the vertical velocity dispersion σ_z.

Testing the initial conditions stability

We attempt to build a stable initial stellar disk to avoid any drastic relaxation or evolution driven by artificial initial conditions.

We ran a control simulation just with the axisymmetric components of the potential model (no spiral arms) for some $5\,\mathrm{Gyr}$, for each galaxy type.

Figure: σ_z as a function of R in the temporal evolution for a Sa, Sb, and a Sc galaxy.

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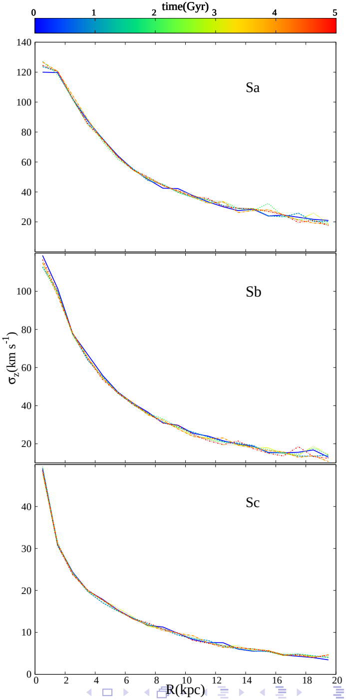
Figure: σ_z as a function of R in the temporal evolution for a Sa, Sb, and a Sc galaxy.

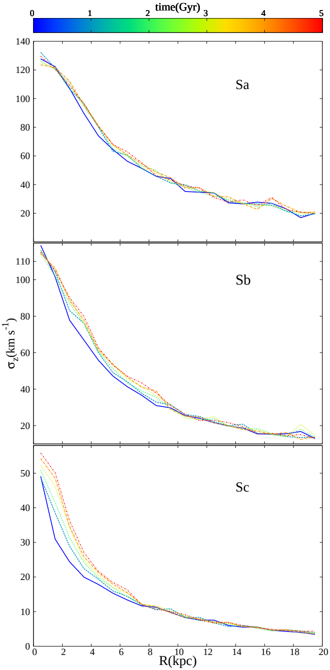


Dependence on the galaxy morphology

Spiral galaxies come in a variety of morphologies, therefore spanning a wide range of values for the parameters that characterise the galaxy type.

The Figure shows σ_z as function of R at different times in the simulation for each galaxy type.
For the simulations the mass of the arms is 5% of the disk mass with a Pitch angle of 40° (Sa), 45°(Sb), and 40° for the Sc galaxy.

There is an increase in vertical dispersion due to the spiral arms. This increase is small for the Sa galaxy and bigger for the Sc galaxy. The later is the galaxy type, the larger is the effect on the disk heating.



In fact for the Sc galaxy we can see the vertical heating directly in the spatial distribution of the disk particles.

Figure: $x - z$ projection of the stellar distribution plotted at $t = 0$, $t = 2.5\mathrm{Gyr}$, and $t = 5\mathrm{Gyr}$. We can see a thickening in the disk during the temporal evolution when comparing with the initial distribution.

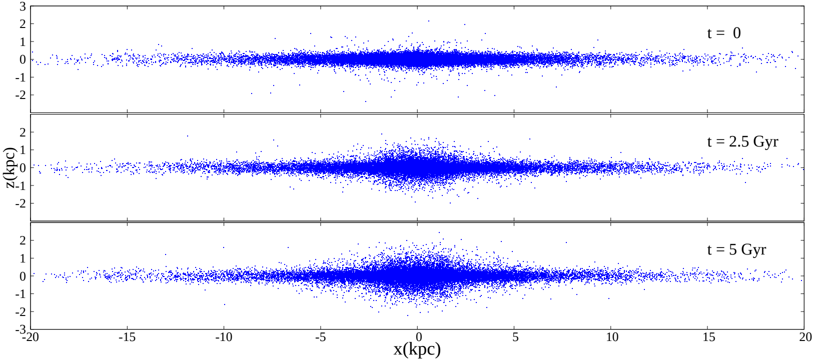
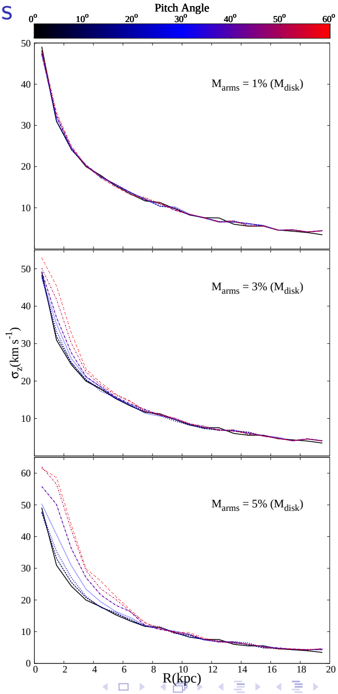


Figure: Edge-on projection of the stellar disk for an Sc galaxy. The spatial distribution of the stars shows a constant heating due to the spiral arms across the entire disk along a $5\mathrm{Gyr}$ evolution.

The pitch angle and the mass of the arms



The pitch angle is one of the parameters that characterise the spiral pattern. We explore a range of values in order to quantify the dependence of the increment in vertical velocity dispersion with the pitch angle.

We show σ_z vs R, where the mass of the arms is kept constant for each plot and the pitch angle variates.
Each plot has the final dispersion $\sigma_z(R, t = 5\,\mathrm{Gyr})$ for every pitch angle value.

It is clear that both parameters, the pitch angle and the mass of the arms, are important for a disk thickening effect driven by the spiral structure.

Varying the angular speed of the spiral pattern

Now we vary the pattern speed in order to find a possible relationship with the vertical heating.

Next Figure shows the evolution of the vertical velocity dispersion σ_z with time up to $5\,\mathrm{Gyr}$ for different values of the pattern speed Ω, for a Sc galaxy.

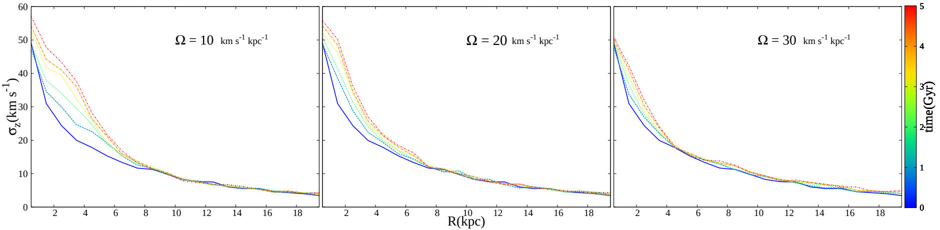


Figure: Time evolution of the vertical velocity dispersion for three different spiral pattern's angular speed in a Sc galaxy. This comparis
shows that slowly rotating spiral arms heats more efficiently the stellar disk.

Here we show the final stage of σ_z across the entire disk for each one of the pattern speeds used.

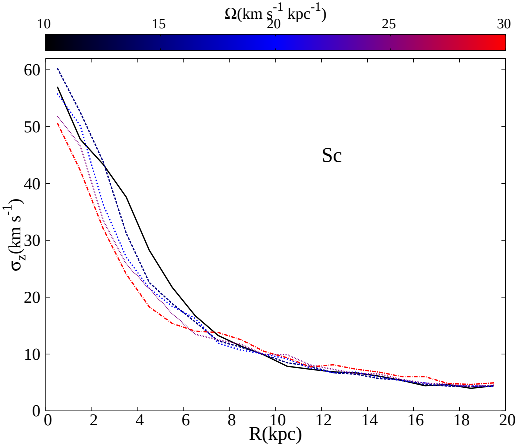


Figure: Final velocity dispersion after a 5 Gyr evolution for different spiral pattern's angular speed in a Sc galaxy.

As expected, the final vertical velocity dispersion and disk thickness are bigger for slow rotating arms, independently of galaxy type.

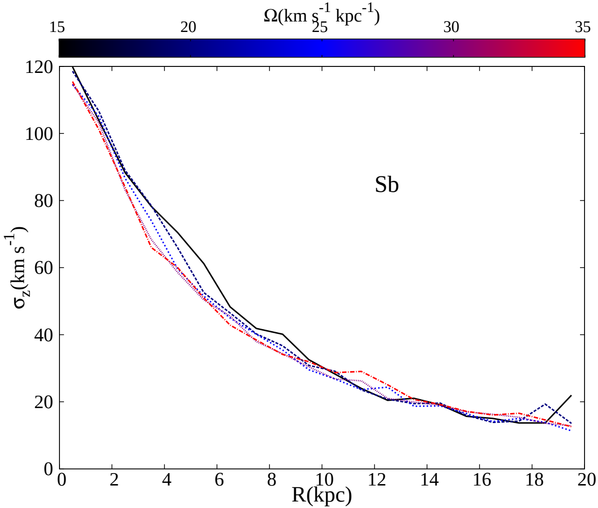


Figure: Final velocity dispersion after a 5 Gyr evolution for different spiral pattern's angular speed in a Sb galaxy.

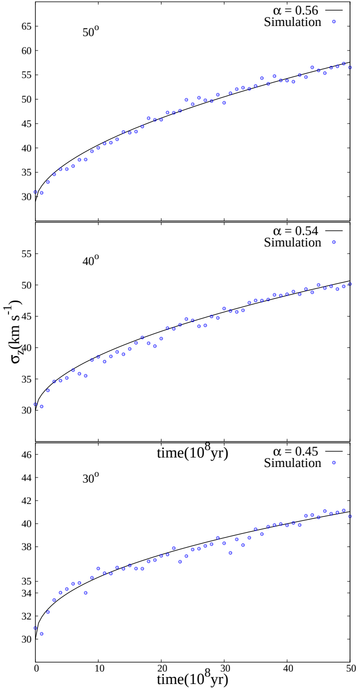
Small values of Ω allow the spiral arms to heat more efficiently the stellar disk.

σ_z – *Time* relation

- It is well known that the age and velocity dispersion of stars are correlated.
- This has been established from observations in the solar neighbourhood Holmberg et al. 2009.
- The σ - t relation shows a smooth, general increase of the velocity dispersion with time and is best parametrized by a power law (Gerssen & Shapiro 2012).

We show the evolution of σ_z with time at different pitch angles: 20^o, 30^o, 40^o and 50^o. The black line is the best fit of the data with a power law $\sigma_z \propto t^{\alpha}$.

α depends only on the Pitch angle. In our simulations α varies within the range 0.27 – 0.56 for a Sc galaxy.



For Sb galaxies a power law also fits well the data.

Remembering that the pitch angles we are working with are not arbitrary, but are the allowed values for each kind of galaxy, we could say that the values of α presented here give us bounds for the contribution of the spiral arms to the vertical velocity dispersion of stars in each galaxy type.

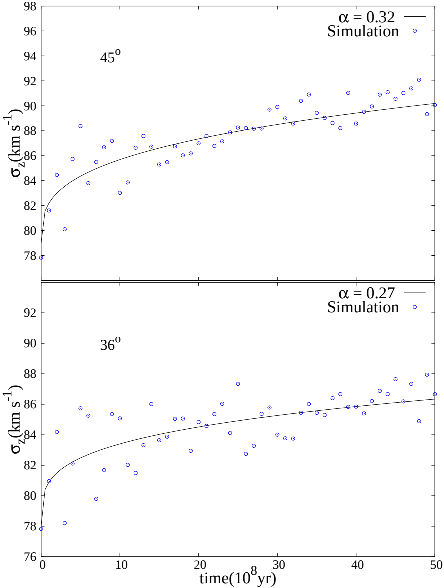


Figure: Time evolution of σ_z for a Sb galaxy at two different pitch angles, 45^o (top) and 36^o (bottom). Black lines show the best fit of the data for a relation $\sigma_z \propto t^{\alpha}$.

The case of the Milky Way

We study the case of the Milky Way galaxy an quantify the response of the stellar disk to spiral arms.

The parameters of the model are constrained by recent estimates of the galactic rotation curve. Meanwhile we adopt a pitch angle of 15.5° for the spiral arms and a mass $M_{arm} = 3\% M_{disk}$.

For a first simulation we don't include a bar in order to isolate the influence of the spiral pattern.

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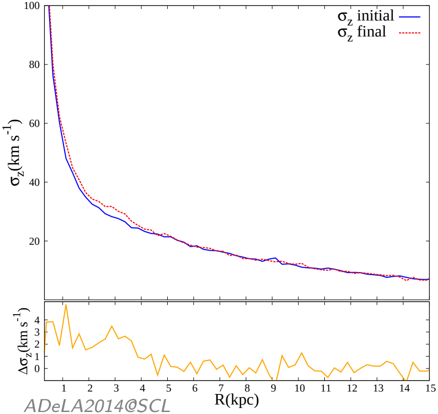

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Plotting the difference between σ_z initial and final we see that the main heating is produced in the innermost region of the disk.

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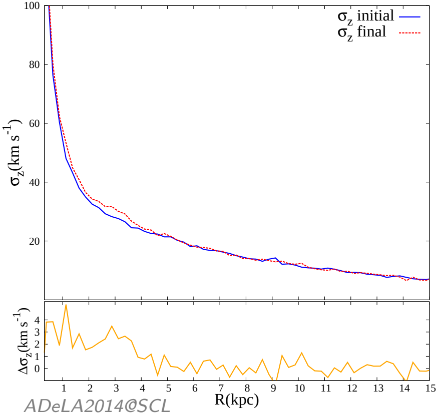

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With this experiment we found that the vertical heating that the Galactic spiral pattern can produce in the Milky Way is minimum and located in a small radial region.

But the spiral arms are not the only non-axisymmetric structure that drives the secular evolution in the Milky Way.

The galactic bar has been proposed as one of the heating mechanisms of disk stars, mostly in the inner region of the disk (Saha et al. 2010).

If the spiral arms are not responsible for the thickness of the Milky Way disk, could it be attributed to the galactic bar?.

This model (Pichardo et al. 2003) not only includes the spiral arms but also a bar, we ran a simulation that evolves the stellar disk into the gravitational potential of this two non-axisymmetric structures with the parameters adjusted to those of the Milky Way.

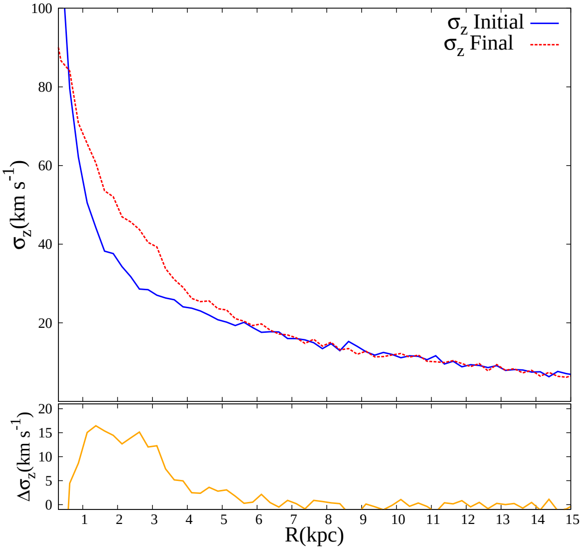

Figure: Heating due to Milky Way Spiral Arms + Bar. Top: Initial and final σ_z. Bottom:$\Delta\sigma_z$ (final-initial).

The effect of the bar is noticeable, with an increase in σ_z up to $16kms^{-1}$ and mostly in the inner $6\mathrm{kpc}$ of the disk.

Summary & Conclusions

It is sometimes believed that the spiral structure cannot excite velocities in the z-direction. Here we found the opposite by considering a 3-D spiral pattern with gravitational potential based on a mass distribution.

By isolating the effect of the spiral arms on the vertical velocity dispersion, we can say that this structure has the potential to be an important heating mechanism that gives raise to a thick disk. But this effect can be either negligible or very important, and strongly depends on the characteristics of the spiral pattern.

By covering a whole set of values for this parameters we conclude that:

- The relative increase in vertical velocity dispersion grows with the morphological type being smaller for Sa galaxies and bigger in Sc galaxies.
- Massive arms and/or large pitch angles are responsible for the most prominent disk thickness found in our simulations.
- Small values of Ω allow the spiral arms to heat more efficiently the stellar disk, independently of galaxy type.
- This heating follows a power law $\sigma_z \propto t^{\alpha}$ as seen from observations in the solar neighbourhood.
- In the case of the Milky Way we found that: The galactic spiral arms by their own are incapable of induce any thickness in the disk, the increase in σ_z is negligible. If we add the galactic bar the vertical velocity dispersion increase considerably, mostly within the region covered by the bar. This means that for the Milky Way the bar is an important heating mechanisms of disk stars.