Scientific report, ESF short visit, Groningen 1-15 November

Project: Constraining the nature of the spiral arms through the velocity distribution function
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Short exchange visit: Groningen (Dr. T. Antoja), 15 days, 1-15 November 2012

The project

Vorobyov & Theis (2008) showed that the convex edges of spiral arms were characterized by quite large negative vertex deviations and considerable positive vertex deviations were seen between the spiral arms. This result was obtained by solving the Boltzmann moment equations up to second order of a two armed spiral model, under several assumptions (e.g thin disc approximation). Recently, in my PhD Thesis, we have generated collisionless n-body simulations that have enough resolution to analyze in detail the kinematics of the galactic disk.

Our preliminary analysis using collisionless n-body and also test particle simulations (kindly provided by T. Antoja), corroborates that the radial and azimuthal gradients of the vertex deviation are well correlated with the non-axisymmetric density structures. Also more interesting, and new, is that the sign of these gradients differs from response spiral arms (induced by the bar in our n-body and test particle simulations) to imposed ones (analytical spiral potentials in test particles). We observe that for simulations with imposed arms there are negative vertex deviations in the trailing part of the arm and positive values in the leading part, while for response arms the behaviour is the opposite.

Is it the behaviour of the vertex deviation a general characteristic of the different types of arms? Is it linked to the nature of the spiral structure? And more important, can this help us to con train the nature of the spiral arms in the Milky Way in the Gaia era, when kinematic information across a large portion of the disc could be obtained? The aim of the visit to the Kapteyn Institute is to analyse in detail these results and try to answer some of these fundamental questions.

Aims of the visit

During this visit to Groningen, we want to accomplish the following goals:

- Use new test particle simulations (Groningen, T. Antoja et al.) to corroborate our results.
- To discuss about the origin of vertex deviation gradients and its dependence on spiral arms nature.
- To establish an error analysis technique to be used to characterize the significance of vertex deviation values.

Teresa Antoja, at Kapteyn Astonomical Institute, has been studying the kinematics of the Milky Way for several years (see T. Antoja, PhD Thesis 2010, Antoja et al 2009, 2010, 2011) and

Test	i(deg)	IC	N(10^6)	Ω_b/corr.	Amp	t_{int}(sp.rot.)
TWA1	8	IC2my	5	20/10.2	13	5
TWA1.1	**15**	IC2my	5	20/10.2	13	5
TWA1.2	8	IC2my	5	20/10.2	13	**2**
TWA1.3	8	IC2my	5	20/10.2	13	**3**
TWA1.4	8	IC2my	5	20/10.2	13	**6.67**
TWA2	8	IC2my	5	**35/6.2**	13	5
TWA2.1	8	**IC2mys10**	5	35/6.2	13	5
TWA2.2	8	IC2my	5	35/6.2	**6**	5
TWA3	8	IC2my	5	**50/4.1**	13	5
TWA3.1	8	**IC2mys10**	5	50/4.1	13	5

Table 1: Non-axisymmetric Galactic Disk Models

she will provide new simulations that will allow us to corroborate our study.

Work carried out during the visit

In these 15 days in the Kapteyn Institute we accomplished several of the goals we proposed in the Short Visit project:

- We ran a set of 10 new test particle simulations and we analyzed them (see Table 1).
- We confirmed the correlation between spiral density perturbations and the vertex deviation gradients and we discussed their origin with the Amina Helmi's group and other professors in the Kapteyn Institute.
- We analyzed the computation of the vertex deviation error (see Equations 2 and 3) and we checked that it takes into account the sampling error (due to the finite particle number) particle number in the region where we are making the analysis and also the sphericity of the velocity distribution. This is important because the origin of the main errors are the low number of particles and the sphericity of the velocity distribution.
- We implemented an error cut in our vertex deviation plots (both in relative and absolute errors). We decided to use the absolute error because takes into account the error from the sampling error and sphericity (it is not the case when using relative error).
- I presented part of my PhD thesis work and the results obtained, in a Kapteyn Institute talk called Wednesday lunch talk.

$$\epsilon^2_{\sigma^2_{ij}} = \frac{\mu_{ijij}}{N} + \mu^2_{ij}\left(\frac{1}{N-1} - \frac{2}{N}\right) + \mu_{ii}\mu_{jj}\left(\frac{1}{N-1} - \frac{1}{N}\right) \quad (1)$$

$$\epsilon_{l_v} = \frac{1}{\sigma_{uv}^2((\frac{\sigma_{uu}^2-\sigma_{vv}^2}{\sigma_{uv}^2})^2+4)}\sqrt{\epsilon_{\sigma_{uu}^2}^2+\epsilon_{\sigma_{vv}^2}^2+\epsilon_{\sigma_{uv}^2}^2(\frac{\sigma_{uu}^2-\sigma_{vv}^2}{\sigma_{uv}^2})^2} \tag{2}$$

Main results

- **Confirmation of differences in the vertex deviation gradient as a function of azimutal angle, when crossing the spiral density perturbations.**
  At the beginning of this Short Visit we discussed the origin of the differences on the vertex deviation gradient that we observed in my master thesis. We concluded that maybe corrotation can play an important role on these differences. It is well known that for spirals departing from the bar, if they have the same pattern speed as the bar, are placed outside corrotation, while the TWA spirals are usually placed inside.
  To test if corrotation is the truly origin of this differences we ran a set of three test particle models, each one of them with the same potential (a TWA spiral, following the Drimmel locus) but changing the pattern speed of the spiral. Doing this we obtained models with a corrotation radius of 4.1, 6.2 and 10.2 Kpc. For that models we also used a small pitch angle (8 deg) to be sure that the spirals will follow the locus and also that they will cross corrotation (for pitch angles higher that 12 it has been observed in Teresa Antoja work that the particles are not able to follow the locus after corrotation).
  The results (see Figure 1) are clear, corrotation is the driver of differences in vertex deviation gradient. As you can see in Figure 1 the vertex deviation gradient sign changes depending in if the density perturbation is inside or outside corrotation (inside corrotation the leading part of the spiral have negative vertex deviations while outside, the vertex deviation in the leading part is positive).

- **Dependence of the results on the initial parameters.**
  We ran several simulations changing the initial parameters one by one (integration time, initial velocity dispersions, spiral amplitude and pich angle) and we found that there are no dependence of the results in the initial parameters.

- **Analysis of new test particle models.**
  We analysed test particle simulations with other spiral arm model which is called PERLAS and we observed that the results are consistent with the ones obtained for the TWA models (see Figure 2, left).
  We also analysed test particle models with no imposed spirals but with an imposed bar potential (quadrupolar bar). In these models we observe that response spiral arms are being formed. We analysed these response spirals and we concluded that on that case we obtain the same results as when we analyse spirals outside corrotation in the TWA models. This result is consistent as we are analysing bar-response spirals (see Figure 2, right).

- **Analysis of N-body models.**
  As a last test we analysed two N-body simulations, one with bar-response spirals (rotating at the same pattern speed as the bar, then outside corrotation), and other with disk-corrotant

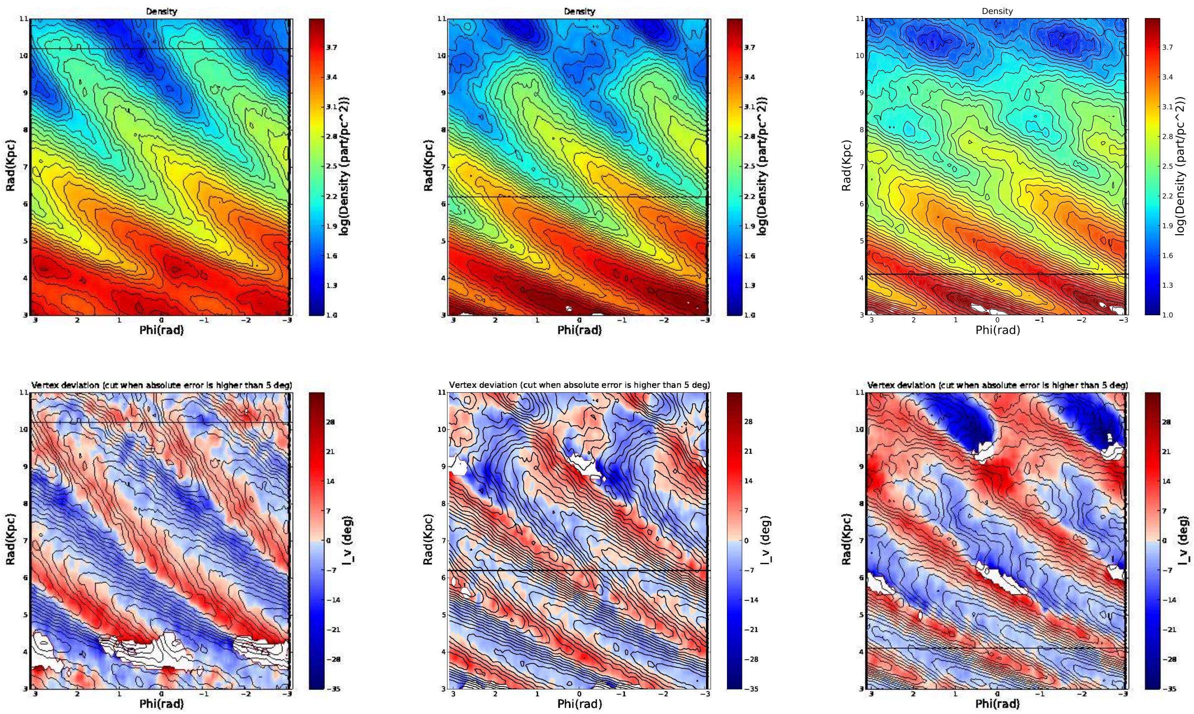

Figure 1: Density and Vertex deviation polar plots for models TWA1, 2 and 3. Black curves are isodensity curves. The galaxy rotate to the right. Horizontal lines are the corrotation radius. White regions correspond to positions where the vertex deviation errors are higher than 5 degrees.

spirals.

The results are again consistent with the previous ones: for the bar-response spirals we observed the same behaviour as in the outside corrotation TWA cases (see Figure 3 left), for the disk corrotant spirals we observe no general correlations between vertex deviation and density structures (see Figure 3 right).

Future collaboration with host institution

It is our interest to continue the work presented here and some others that can derive from it, in collaboration with T. Antoja from Kapteyn Institute and also with some of her collegues.
We will apply for some new Short Visit Grants or other kind of grants, in the near future, to go deeply on this collaboration.

Projected publications

We started to write a draft to report the results we obtained on that Short Visit. We will acknowledge the ESF for this Short Visit Grant in the resulting publication.

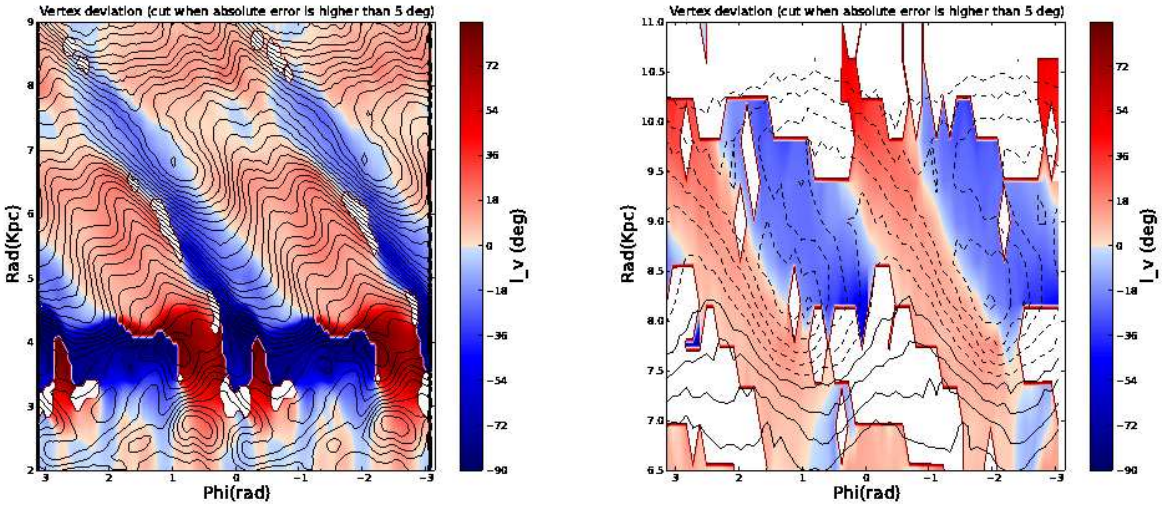

Figure 2: Vertex deviation polar plots. Left: Test particle model with imposed PERLAS spiral potential. Right: test particle model with imposed quadrupole bar potential. The black lines are isodensity curves. In both cases the galactic model rotates to the right. White regions correspond to positions where the vertex deviation errors are higher than 5 degrees.

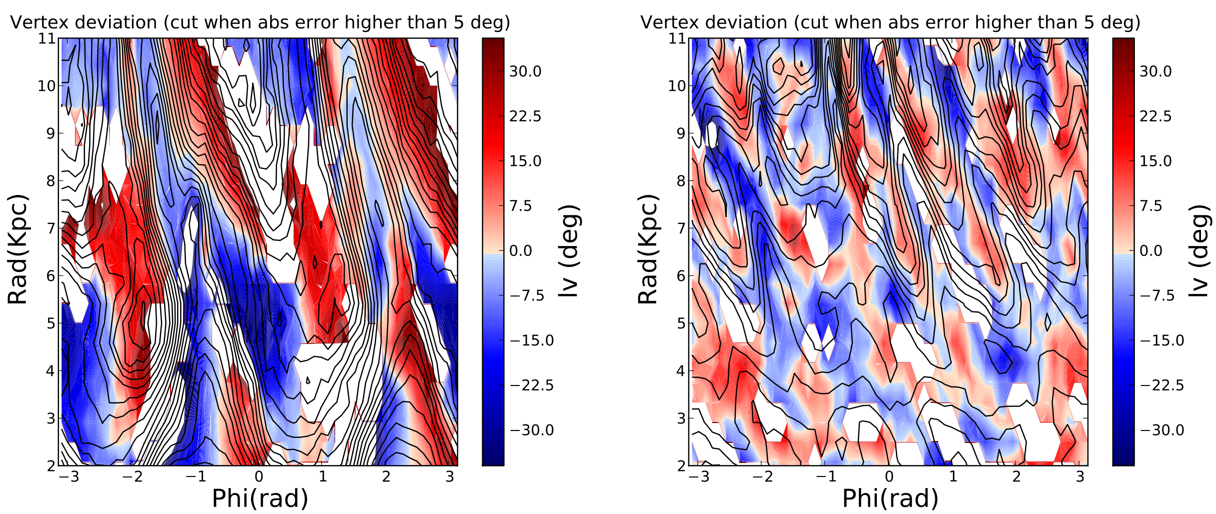

Figure 3: Vertex deviation polar map for a spiral bar-response N-body model (left) and disk corrotant (right). Black lines are isodensity curves. The galaxy rotates to the right. The bar ends at 6 Kpc. White regions correspond to positions where the vertex deviation errors are higher than 5 degrees.