Coupled & decoupled bar plus spiral galaxy model simulations

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1 Preface

This document aims to gather some of the results obtained using the bar-spiral model simulation and attempt to explain these as well as potential research that can be continued.

Following the research done by Hunt et al[1], the graphs in this document model coupled and decoupled scenarios of bar and spiral galaxies. Different bar sizes and spiral and bar frequencies were tested to find potential similarities with the Milky Way. The wrappers used in the code assume a flat rotation curve, the solid-body rotation wrapper treats the potential as a rigid body, where all points move at the same velocity. The corotation wrapper is acted on the spiral potential only and forces the spiral arms to co-rotate everywhere[2].

Figures with subplots all show (from left to right) increasing spiral arm lifetimes (L) and (top to bottom) decreasing times since the peak of the spiral arm density (t_{peak}). They all show how specific parameters used on the potentials affect the UV plane in the solar neighbourhood.

2 Long-slow bar and spiral potential

The following graphs were made using the long slow bar model, where the bar radius was set to 5kpc and the rotational frequency to $0.029 Gyr^{-1}$ (as defined by Hunt and Bovy)[3].

2.1 Solid-Body Rotation Wrapper

These figures show decent differences in morphology between the coupled and decoupled models at around $t_{peak} = -0.86$ and L=-160 Myr. The solid-body rotation wrapper is the most physically unrealistic model, however it is also the simplest one to analyse. By simplifying the potentials to represent a rigid body, the distinction between coupled and decoupled scenarios may have become much clearer. These parameters could potentially be explored further using more accurate models.

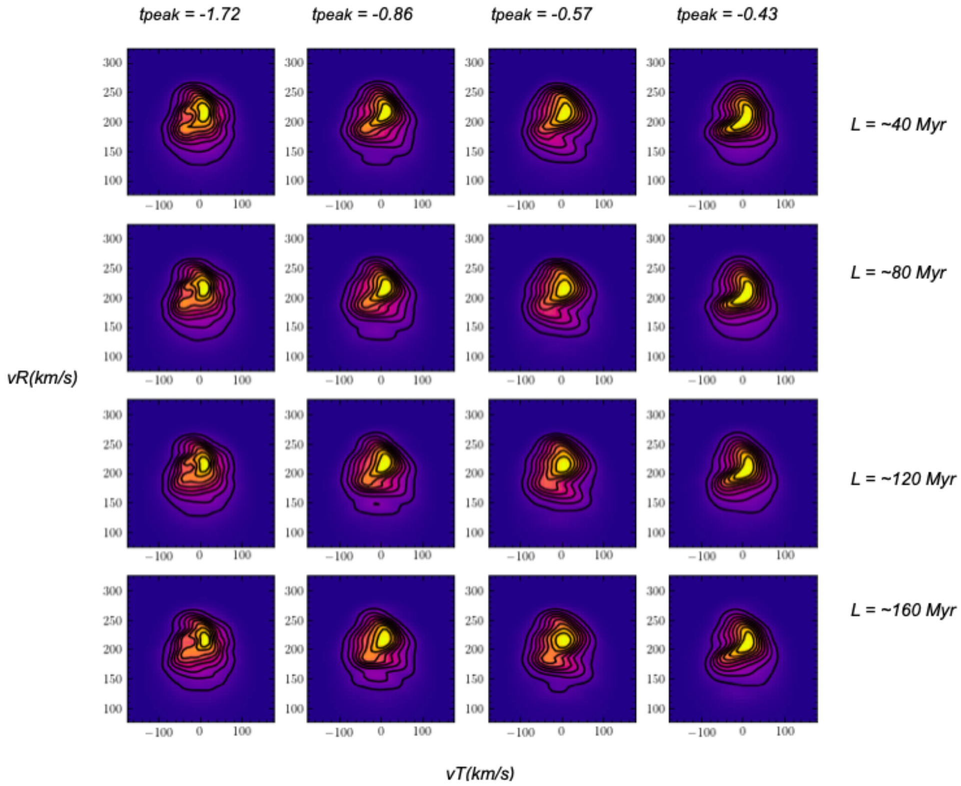

Figure 1: Set of 16 decoupled models. Rotational frequency of the spiral: $0.167Gyr^{-1}$

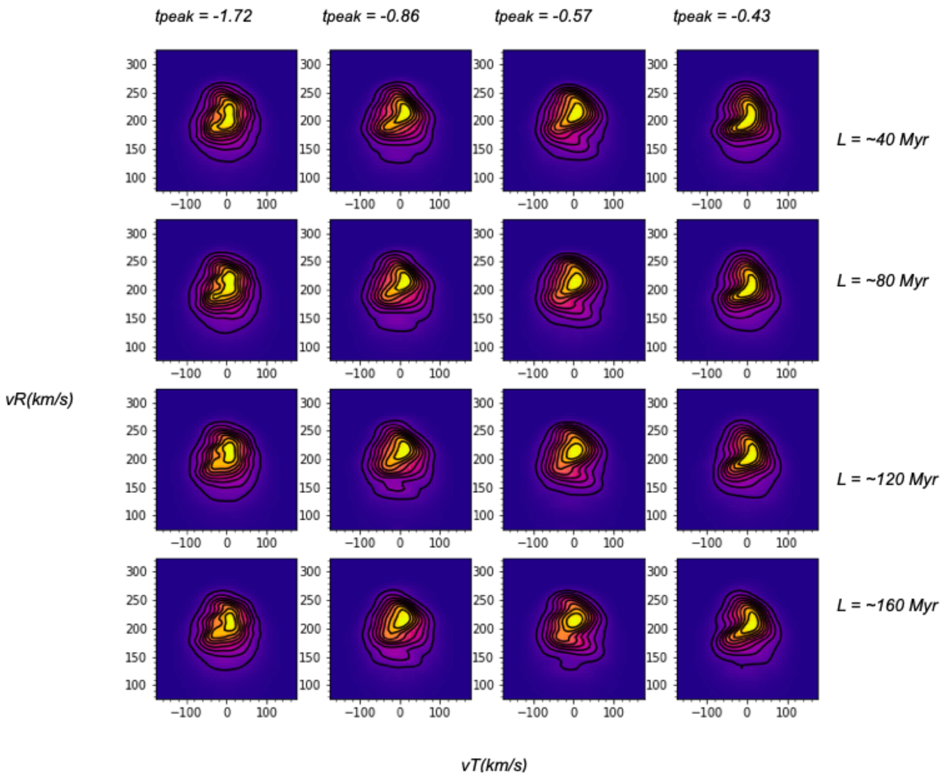

Figure 2: Set of 16 coupled models, both bar and spiral have a rotational frequency of $0.029Gyr^{-1}$

2.2 Solid-Body Rotation and Corotation Wrapper

Using the corotation wrapper results in a more physically accurate set of models.

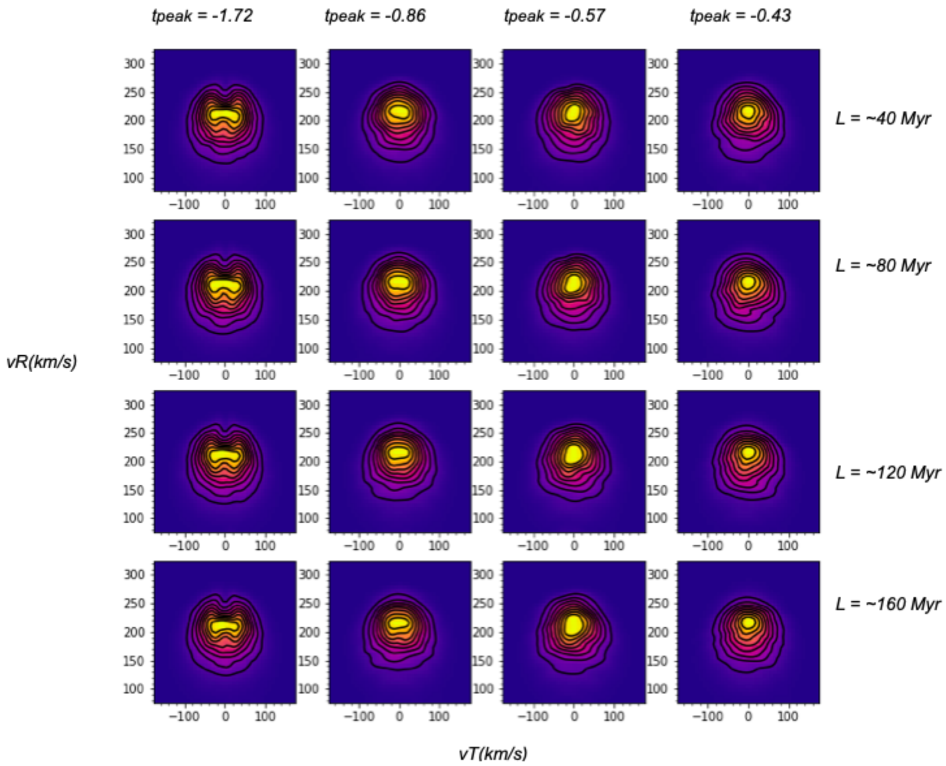

Figure 3: Set of 16 decoupled model. Frequency of the spiral: $0.167 Gyr^{-1}$

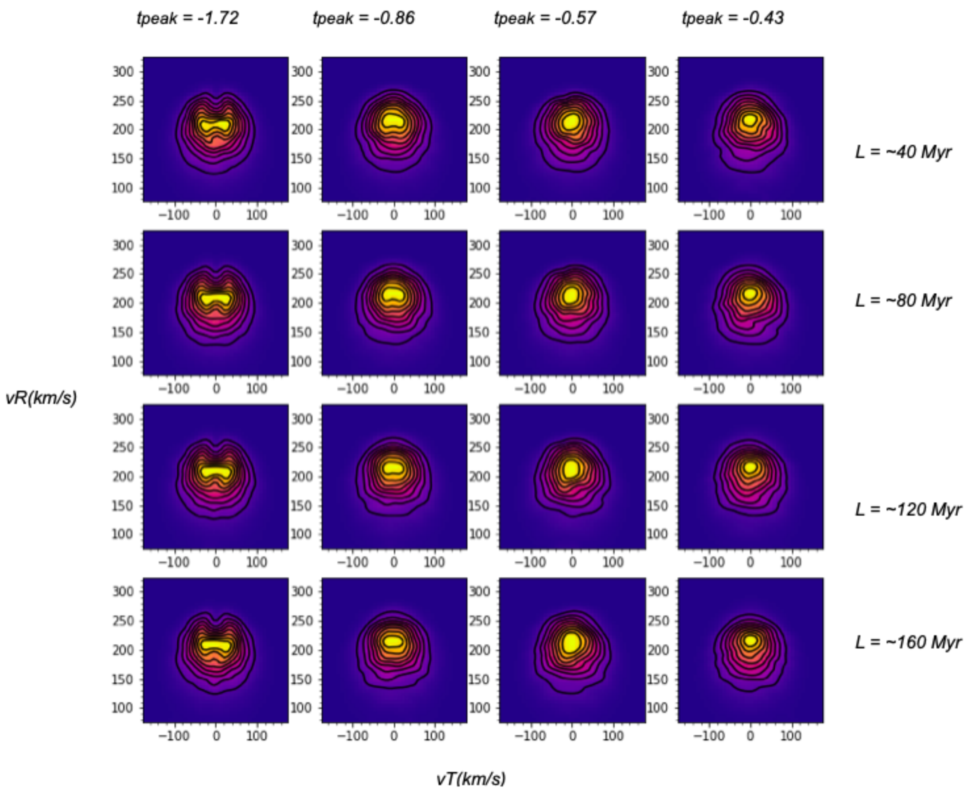

Figure 4: Set of 16 coupled model, both bar and spiral have a rotational frequency of $0.029 Gyr^{-1}$

2.3 Analysis

The anomalous shape in the $t_{peak} = -1.72Gyr$ orbits for the decoupled models was further analysed by looking at the individual orbits in the solar neighbourhood. Monari et al[4] show a potentially similar elliptical shape in the orbits in their figs. 4-7 for spiral-bar decoupling.
Below are the integrated orbits for the long slow bar model with different parameters and wrapper combinations.
A closer look at individual orbits at several t_{peak} shows the models made with the solid body rotation wrapper are unrealistic as it forces both the bar and spiral to act on the orbits in a similar way. Below are two examples of over plots of orbits for the individual and decoupled models with the long slow bar.

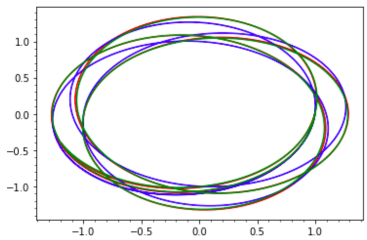

Figure 5: Orbits in a spiral potential(red), bar potential (blue) and combined potentials (green) for $t_{peak} = -0.86$ and L=40Myrs

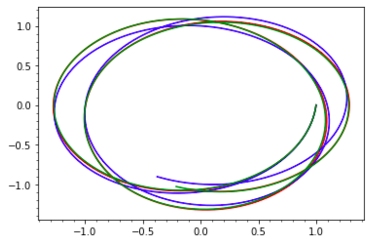

Figure 6: Orbits in a spiral potential(red), bar potential (blue) and combined potentials (green) for $t_{peak} = -0.53$ and L=120Myrs

Looking at the same orbits but with models where the corotation wrapper was used the orbits seem more realistic and show a variation in shape depending on the potential that was used.

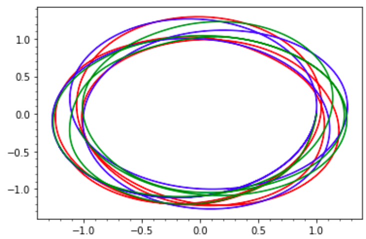

Figure 7: Orbits in a spiral potential(red), bar potential (blue) and combined potentials (green) for $t_{peak} = -0.86$ and L=40Myrs

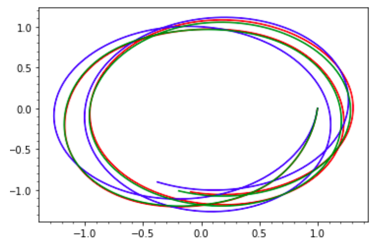

Figure 8: Orbits in a spiral potential(red), bar potential (blue) and combined potentials (green) for $t_{peak} = -0.53$ and L=120Myrs

3 Short-fast bar and spiral potential

The short fast bar model sets the bar radius as 3.5kpc and the rotational frequency as $0.041Gyr^{-1}$ (as defined by Hunt and Bovy)[3].

3.1 Solid-Body Rotation Wrapper

Again the clearest differences in morphology are shown along the $t_{peak} = -0.86$ models, L=-120 Myr seems to show the most visible difference in morphology. Although not a realistic simulation, modelling the spiral-bar structure with this wrapper could potentially indicate the most likely parameters to explore orbits for coupled and decoupled models.

It must be noted that the models made with solid body wrapper on the spiral potential were concluded to be unrealistic, however, the graphs in section 3.1 were included for completeness. These models are therefore not accounted for in the final analysis in section 3.3.

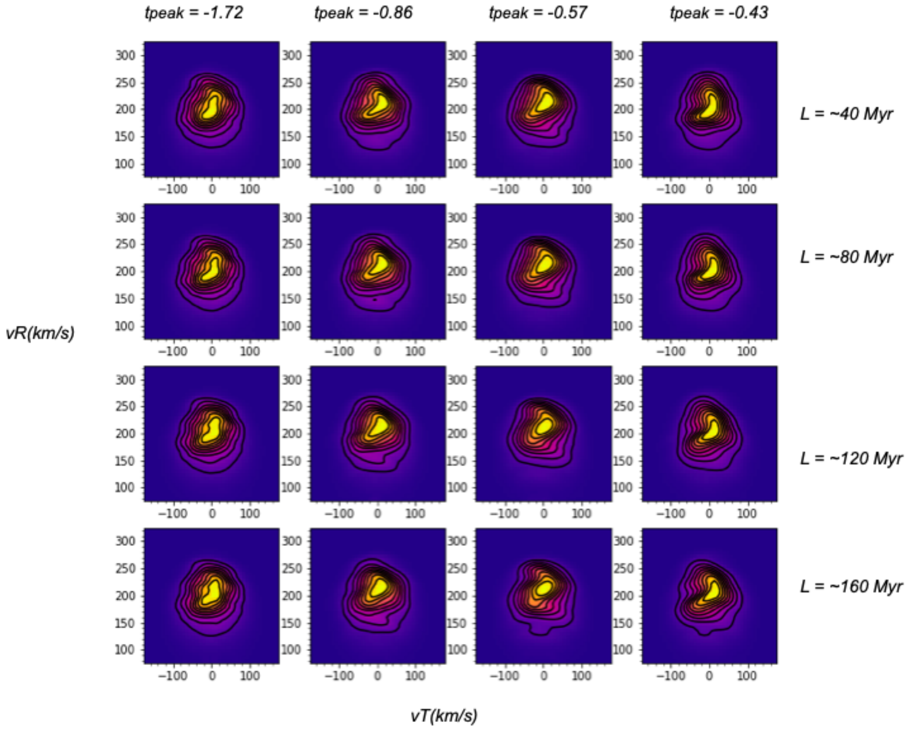

Figure 9: Set of 16 coupled models, both bar and spiral have a rotational frequency of $0.041Gyr^{-1}$

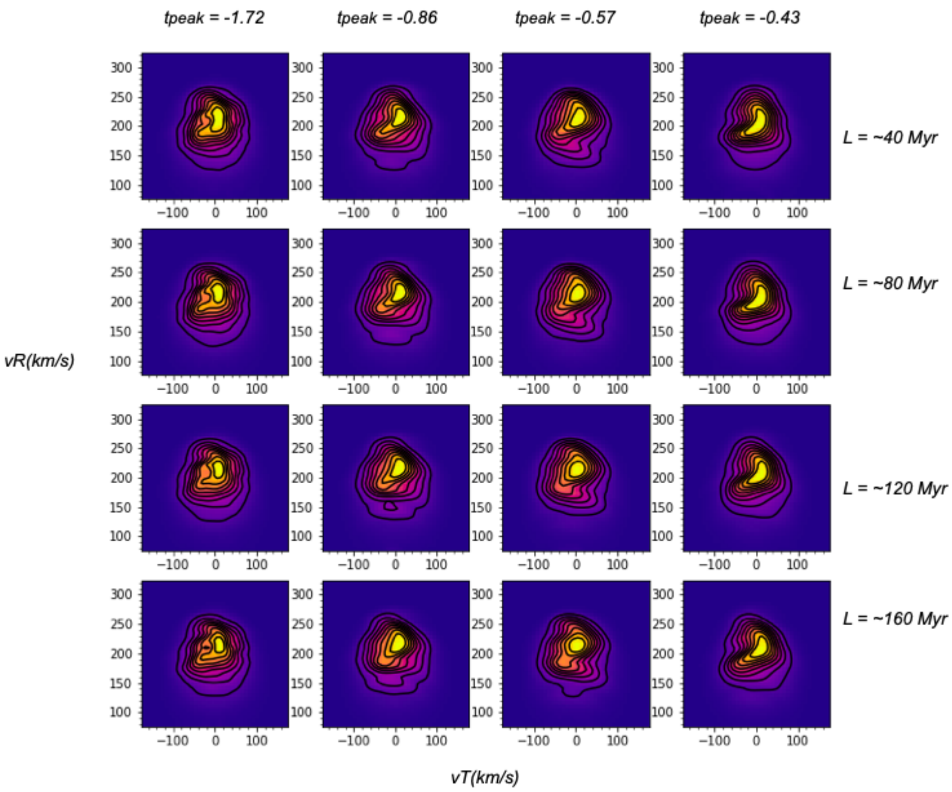

Figure 10: Set of 16 decoupled models, spiral has a rotational frequency of $0.022Gyr^{-1}$

3.2 Solid-Body Rotation Wrapper and Corotation Wrapper

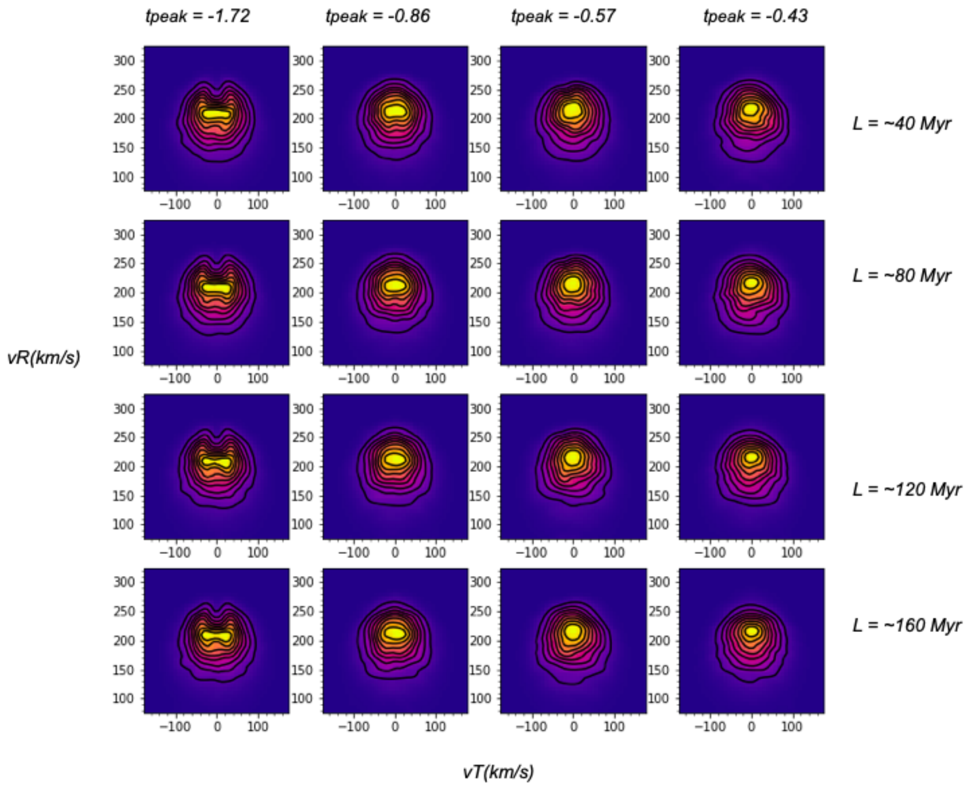

Figure 11: Set of 16 coupled models, both bar and spiral have a rotational frequency of $0.041Gyr^{-1}$

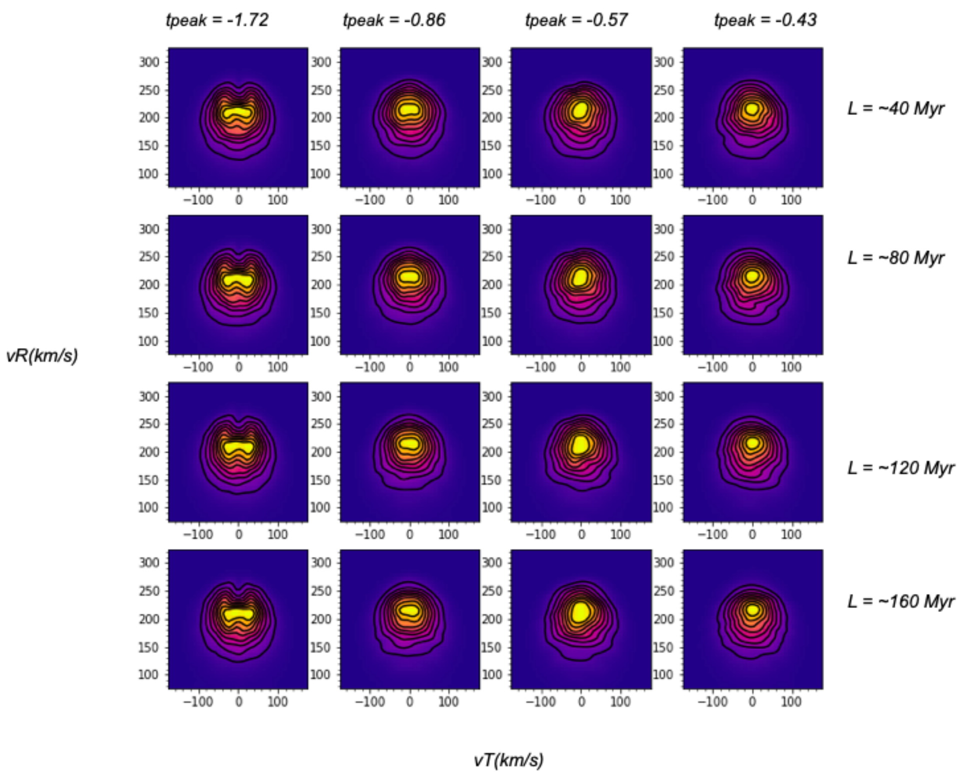

Figure 12: Set of 16 decoupled models, spiral has a rotational frequency of $0.022Gyr^{-1}$

3.3 Analysis

From the sets of graphs shown in sections 2.2 and 3.2 it can be seen that changing the frequency and length of the bar doesn't cause an significant changes to the resulting graphs. It can therefore be concluded that the main source of perturbations in these models is the spiral structure, and as such these may be useful in attempting to understand the spirals in the Milky Way.

Below are the over plotted orbits in the x-y plane for a decoupled scenario with $t_{peak} = -0.86$ and L=40Myrs. These orbits also show no significant difference compared to those produced using the long slow bar model in section 2.3 and so show further evidence of how significant the spiral potential is within the model.

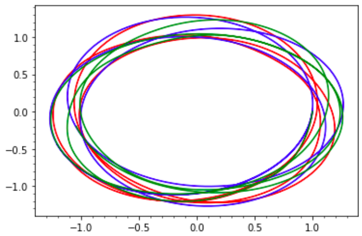

Figure 13: Orbits in a spiral potential in the solid body rotation wrapper (red), bar potential (blue) and combined potentials (green).

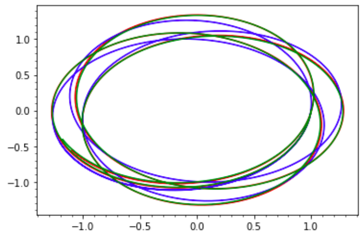

Figure 14: Orbits in a spiral in the corotation wrapper potential(red), bar potential (blue) and combined potentials (green).

Because of how prominent the perturbations from the spiral potential are in the models, the anomalous shape of the orbits at $t_{peak} = -1.72Gyr$ could be the result of the spiral structure disturbing the orbits by passing over the solar neighbourhood ultiple times. With each pass of the spirals the disturbance gets 'recorded' as a visible perturbation. In comparing the models with the Gaia DR2 orbits, the clear differences show the spirals in the Milky Way may be younger than 1 Gr. It must be noted that this model assumes the existence of only one set of spirals, which may not be the case in reality.

4 Observational Data

Figs. 15 and 16 show the tangential vs radial velocities of a subset of stars using the Gaia Data Release 2 (GDR2). Both these graphs were plotted over the ones produced by the simulation in order to find similarities.

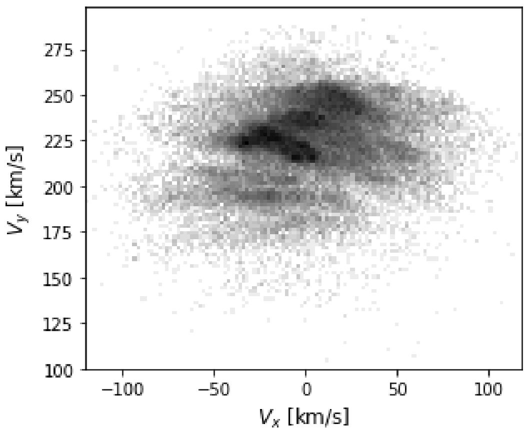

Figure 15: V_T vs V_R in the Gaia plane for the observational data from GRD2

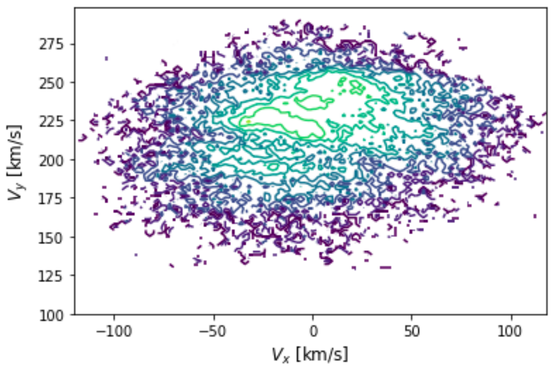

Figure 16: V_T vs V_R in the Gaia plane for the observational data from GRD2

To test the models, contour plots such as the one in fig. 16 were plotted over the graphs made with the simulation (see Appendix fig. 19). It was observed that the $t_{peak} = -0.43$ models showed the best fit and so the contour of L=40 was plotted over the observed (fig 18). The simulation shows some similarities but none significant enough to make the simulation be an adequate depiction of our galaxy. The plot was also compared to a model made with the Dehnen bar[5] rotating at an equal frequency (fig. 17). The similarity between fig. 17 and the observed data is fairly clear, however it was concluded from the simulation that the bar had less effect on the solar neighbourhood than the spiral, this may be due to how the fat that a flat rotation curve was assumed which simplifies the physics involved in the rotation of the structures.

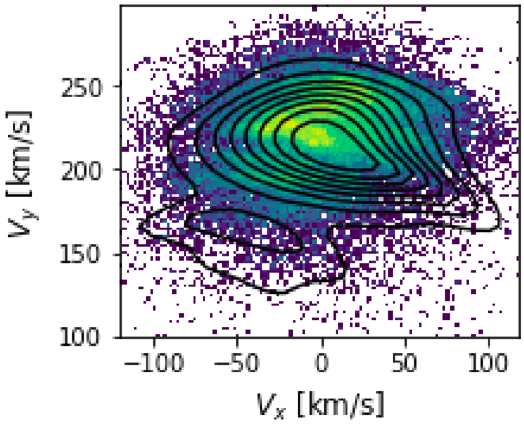

Figure 17: Contour plot of tangential vs radial velocities for a model with a long-slow Dehnen bar over the observed Gaia data

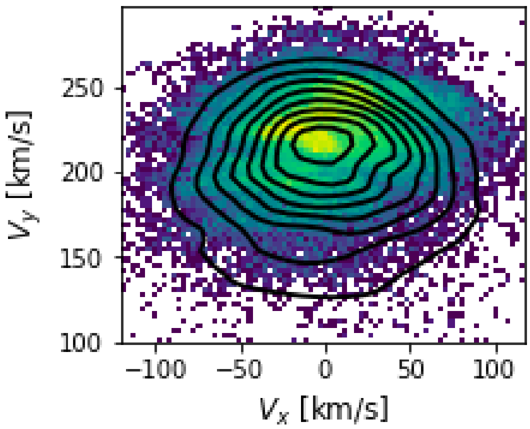

Figure 18: Contour plot of tangential vs radial velocities for a model with a long-slow bar and spiral at L=40 and $t_{peak} = -0.43$ over the observed Gaia data

Overall, although the models made with the simulation do not present the same features as the ones seen with observed data, they can present a simplified version of complex structures. This can be useful in narrowing down theories and be used to improve future simulations.

5 Appendix

NOTE: The v_R vs v_T graphs in sections 1-3 are incorrectly labelled, such that v_R should be on the x-axis and v_T on the y-axis.

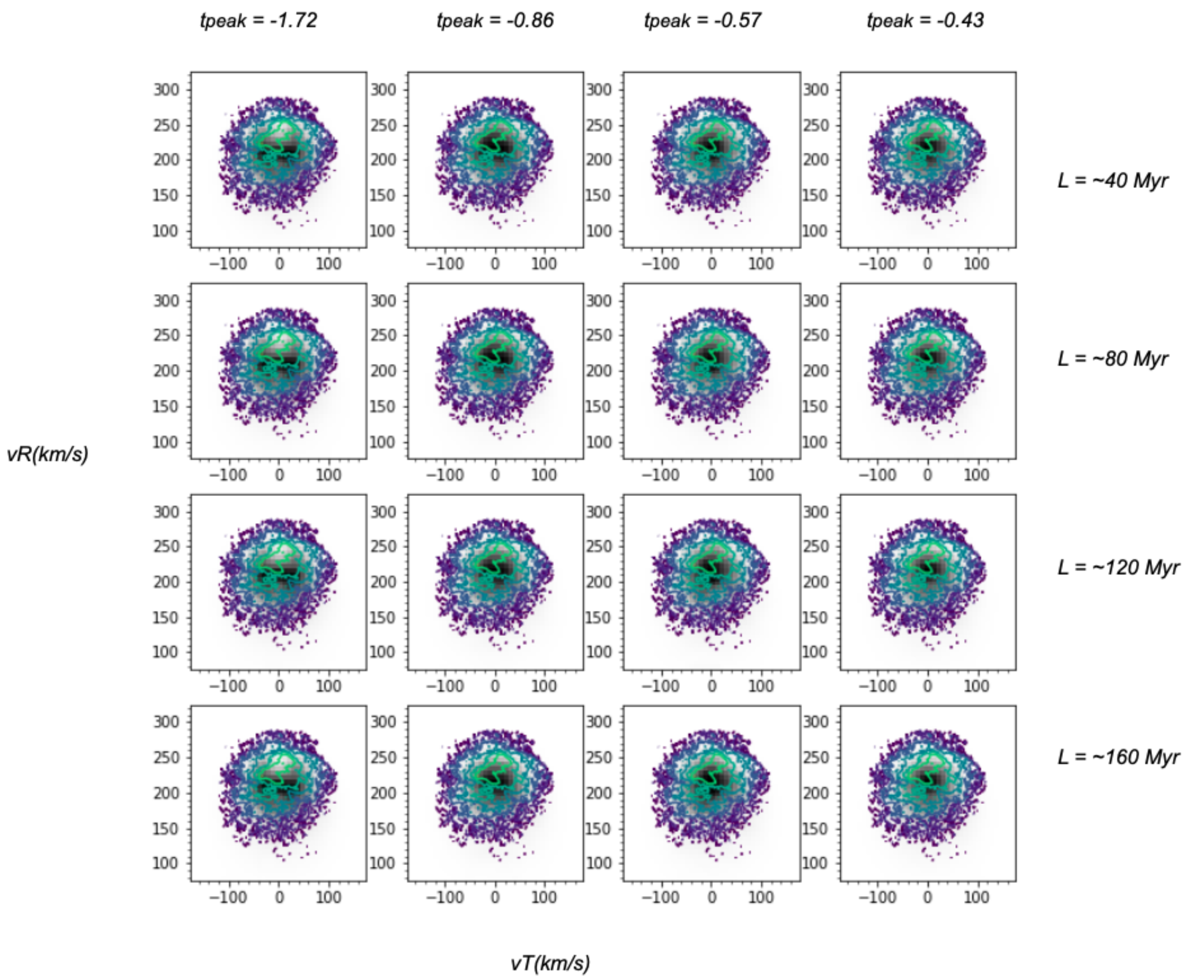

Figure 19: Graph showing the observed data from GDR2 as contours and the resulting o

References

1. Hunt, J. A. S., Hong, J., Bovy, J., Kawata, D. & Grand, R. J. J. Transient spiral structure and the disc velocity substructure in Gaia DR2. *Monthly Notices of the Royal Astronomical Society* **481,** 3794–3803. ISSN: 1365-2966. `http://dx.doi.org/10.1093/mnras/sty2532` (Sept. 2018).
2. Bovy, J. galpy: A python LIBRARY FOR GALACTIC DYNAMICS. *The Astrophysical Journal Supplement Series* **216,** 29. ISSN: 1538-4365. `http://dx.doi.org/10.1088/0067-0049/216/2/29` (Feb. 2015).
3. Hunt, J. A. S. & Bovy, J. The 4:1 outer Lindblad resonance of a long-slow bar as an explanation for the Hercules stream. *Monthly Notices of the Royal Astronomical Society* **477,** 3945–3953. ISSN: 1365-2966. `http://dx.doi.org/10.1093/mnras/sty921` (Apr. 2018).
4. Monari, G. *et al.* The effects of bar–spiral coupling on stellar kinematics in the Galaxy. *Monthly Notices of the Royal Astronomical Society* **461,** 3835–3846. ISSN: 1365-2966. `http://dx.doi.org/10.1093/mnras/stw1564` (June 2016).
5. Dehnen, W. The Effect of the Outer Lindblad Resonance of the Galactic Bar on the Local Stellar Velocity Distribution. *The Astronomical Journal* **119,** 800–812. ISSN: 0004-6256. `http://dx.doi.org/10.1086/301226` (Feb. 2000).