The 4:1 outer Lindblad resonance of a long-slow bar as an explanation for the Hercules stream

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ABSTRACT

There are multiple groups of comoving stars in the Solar neighbourhood, which are possible signatures of one of the fundamental resonances of non-axisymmetric structure such as the Galactic bar or spiral arms. One such stream, Hercules, has been proposed to result from the outer Lindblad resonance of a short-fast rotating bar as shown analytically, or the corotation resonance of a longer slower rotating bar as observed in an N-body model. We show that by including an \( m = 4 \) Fourier component in an analytical long bar model, with an amplitude that is typical for bars in N-body simulations, we can reproduce a Hercules-like feature in the stellar kinematics of the Solar neighbourhood. We describe the expected symmetry in the velocity distribution arising from such a model, which we will soon be able to test with Gaia.

Key words: Galaxy: bulge – Galaxy: disc – Galaxy: fundamental parameters – Galaxy: kinematics and dynamics – solar neighbourhood – Galaxy: structure.

1 INTRODUCTION

The kinematics of the Solar neighbourhood shows rich substructure in the form of streams or moving groups. One such stream, Hercules, consists of stars with \( U \approx -30 \) km s\(^{-1}\) and \( V \approx -50 \) km s\(^{-1}\) with respect to the Sun’s velocity, where \( U \) is velocity in the direction of the Galactic Centre and \( V \) is velocity in the direction of rotation. It has been proposed that Hercules is a result of the outer Lindblad resonance (OLR) of the Galactic bar (Dehnen 2000). This arises naturally from resonant interaction between the disc and a short (e.g. \( \sim 3.5 \) kpc) fast rotating bar, as further explored in e.g. Antoja et al. (2014) and Monari et al. (2017).

However, if the bar is longer (e.g. \( \sim 5 \) kpc), as favoured by more recent measurements of its extent (e.g. Wegg, Gerhard & Portail 2015), then the bar must rotate slower, because the furthest the bar can extend is corotation (e.g. Contopoulos 1980). For such a bar, the OLR is located at a Galactocentric radius of around 10.5 kpc, making it unable to account for the Hercules stream (although note that a possible OLR feature has been observed around 10–11 kpc in Liu et al. 2012).

Pérez-Villegas et al. (2017) present an alternative explanation for the Hercules stream arising from a bar with a half length of 5 kpc. In this model, stars orbiting the bar’s Lagrange points \( L_4 \) and \( L_5 \) move outwards from corotation which occurs at \( R = 6 \) kpc to pass through the Solar neighbourhood. However, explorations of the distribution function in the outer disc for a long-slow bar model, either show no Hercules-like feature (e.g. Monari et al. 2017b), or one which is substantially weaker (Monari et al. 2017a; Binney 2018) than is seen in either the model from Pérez-Villegas et al. (2017), or the Solar neighbourhood. These models typically use a simple quadrupole bar potential (e.g. from Dehnen 2000), which is a simple approximation for the complex structure in the inner Galaxy.

While the exact morphology of the bar is not yet fully constrained, various studies favour a more complicated potential than is given by the Dehnen bar. For example, the Milky Way appears to host an X-shaped bulge (e.g. Ness & Lang 2016) such as is often seen in external galaxies (e.g. Lüttinge, Dettmar & Pohlen 2000) and can be easily created in N-body simulations (e.g. Combes & Sanders 1981; Athanassoula 2005; Abbott et al. 2017). Fourier decomposition of the density distribution in simulated (e.g. Athanassoula & Misiriotis 2002) and observed (e.g. Quillen, Frogel & Gonzalez 1994; Bata et al. 2006; Díaz-García, Salo & Laurikainen 2016) barred disc galaxies show evidence for higher order modes than the \( m = 2 \) Dehnen bar. Thus, it is possible that the long-slow bar scenario does not predict a Hercules-like stream due to the simplicity of the assumed bar potential.

In this work, we show that a long-slow bar such as is shown in Pérez-Villegas et al. (2017) is capable of producing a Hercules-like feature in the Solar neighbourhood \( UV \) plane, where including an \( m = 4 \) Fourier component in the model for the bar potential.

In Section 2, we present seven \( N \)-body galaxy models which show varying bar morphologies and compute the \( m = 4 \) Fourier mode of the bars. In Section 3, we present models of the long bar with and without an \( m = 4 \) component and discuss the impact on the resulting
Table 1. Parameters of the simulations displayed in Fig. 1. For models with a thin and thick disc, the value outside the brackets is the parameter for the thin disc, and the value in the brackets is the parameter for the thick disc.

| Model | $M_{200}$ ($10^{12}$ $M_\odot$) | $M_d$ ($10^{10}$ $M_\odot$) | $c$ | $R_d$ (kpc) | $z_d$ (kpc) |
|-------|-------------------------------|-------------------------------|----|-------------|-------------|
| A     | 2.5                           | 4.0                           | 10.0 | 2.5         | 0.35        |
| B     | 2.0                           | 5.0                           | 9.0  | 3.0         | 0.3         |
| C     | 1.5                           | 4.5(1.5)                      | 12.0 | 4.0(2.5)    | 0.35(1.0)  |
| D     | 1.75                          | 5.0                           | 9.0  | 3.0         | 0.3         |
| E     | 2.5                           | 4.0(1.0)                      | 10.0 | 2.5(2.0)    | 0.3(1.0)   |
| F     | 1.0                           | 5.5(0.5)                      | 10.0 | 3.0(2.5)    | 0.35(1.0)  |
| G     | 2.0                           | 5.0                           | 10.0 | 2.0         | 0.3         |

velocity distribution, both in the Solar neighbourhood and further across the Galactic disc. In Section 4, we discuss the expectation of symmetry in the velocity distribution across the Galactic disc if the bar has an $m = 4$ component. In Section 5, we summarize our results.

2 SIMULATIONS

It is known from observations of external galaxies that within barred spiral disc galaxies the size and shape of the central bar can vary greatly. In this section, we present seven $N$-body models which display different morphological properties and perform a Fourier transform on their central bars to recover the amplitude of the various modes of the radial force.

The set of galaxies were generated with the $N$-body/SPH code GCD+ (e.g. Kawata & Gibson 2003). Most have been examined in other works, in which details of the numerical simulation code and the set-up procedure can be found. Table 1 shows the basic parameters where $M_{200}$ ($M_\odot$) is the total halo mass, $M_d$ ($M_\odot$) is the mass of the stellar disc, $c$ is the concentration parameter, $R_d$ (kpc) is the scale length of the disc, and $z_d$ (kpc) is the scale height of the disc. For models including a thick disc, the parameter for the thick disc is shown in brackets after the thin disc entry.

Fig. 1 shows the face-on (left) and edge-on (right) morphology of model galaxies A to G (top to bottom). Model A [which was previously analysed in Kawata et al. (2014) and Hunt et al. (2015)] contains a short flat bar, with strong spiral structure, and is comprised of a single thin disc. Model B (previously analysed as Target II in Hunt, Kawata & Martel 2013) contains a long flat bar, with light spiral structure, and is comprised of a single thin disc. Model C (previously analysed in Kawata et al. 2017) contains a long flat bar, with light spiral structure and is comprised of a thin and thick disc. Model D (previously analysed as Target IV in Hunt et al. 2013) contains a short bar, with little spiral structure, and is comprised of a single thin disc. Model E contains a long flat bar and is composed of a thin and thick disc. Model F contains a short bar and is comprised of a thin and thick disc. Model G contains a short bar, with light spiral structure, and is comprised of a single thin disc. Models D, F, and G have a pronounced X shape when viewed edge on, whereas models A, C, D, and E do not contain an X-shaped central structure.

Fig. 2 shows the Fourier decomposition of the radial force of the region dominated by the bar, using the simple cut of $R_G \leq 5$ kpc, by distance from the galactic centre (left) and by angle at 8 kpc (right) of model galaxies A to G (top to bottom) for $m = 2$ (blue solid), $m = 4$ (green dashed), $m = 6$ (red dash–dotted), and $m = 8$ (black dotted). The radial force at the Solar radius calculated from the bar region is dominated by the $m = 2$ mode, with the force ranging from around 1.5 per cent to 4 per cent of the total force coming from the $m = 2$.
The $m = 4$ bar component of the bar, compared with the axisymmetric background at $R_0$. All models except G have a visible $m = 4$ component, albeit substantially weaker than the $m = 2$ mode. The force contribution from the $m = 4$ component ranges from 0.1 per cent to 0.4 per cent of the total force in models A–F. Model G does contain an $m = 4$ force component, but it is a magnitude smaller than in the other models. In general, the amplitude of the $m = 4$ component of the radial force is around $5-10$ per cent of the amplitude of the $m = 2$ component. It is also worth noting that each simulation examined here contains a negative $m = 4$ component, e.g. the maximum of the $m = 2$ mode aligns with a minimum of the $m = 4$ mode. We are not suggesting that all $m = 4$ components are negative, it is merely the case for this set of models. For example, Buta et al. (2006) show that the fraction of positive and negative $m = 4$ components (shown as the phase angle in their fig. 3) is equal in a sample of 26 early-type disc galaxies. Note that in all of these observed galaxies the offset in the phase angle of the $m = 2$ and $m = 4$ components is approximately either $0^\circ$ or $90^\circ$; for example, they are consistently aligned.

Figs 1 and 2 do not indicate a strong link between a bar containing significant vertical structure such as an X shape, and the density or radial force having a large $m = 4$ component. However, there is a slight correlation in the strength of the $m = 4$ component. For example, models A, B, C, and E, all contain flat bars, and while they are dominated solely by the $m = 2$ bar, they contain $m = 4$ components of similar amplitudes. Models D, F, and G contain X-shaped structure, and while they also contain $m = 4$ components, in models D and F the amplitude is slightly less than in the flat bars, and model G has very little or no $m = 4$ component. The correlation here is slight, and it would require further study to determine if such features are more likely to be found together, separately, or are entirely uncorrelated. Nevertheless, we take the presence of $m = 4$ components in the flat bar models as sufficient justification to explore the effect of the $m = 4$ component in a two-dimensional model in Section 3. The models also contain small $m = 6$ and $m = 8$ components, but at a much lower amplitude.

### 3 MODELLING THE HIGHER ORDER FOURIER COMPONENTS OF THE BAR

To make predictions of the velocity distribution in the Solar neighbourhood resulting from resonant interaction with the Galactic bar, we use `galpy` (Bovy 2015) to simulate the stellar orbits. We choose to investigate the effects of including an $m = 4$ component in the bar potential because it is the most significant of the higher order modes, and because for some long-slow bar models the 4:1 OLR occurs around the location of the Sun (e.g. $\sim 8$ kpc in Li et al. 2016).

As mentioned, because the simulations in Section 2 show the $m = 4$ component can occur in a flat bar, we ignore the vertical motions and only simulate the two-dimensional dynamics in the Galactic plane. As in Bovy (2010) and Hunt et al. (2018), we use a Dehnen distribution function (Dehnen 1999) to model the stellar disc before bar formation and represent the distribution of stellar orbits. This distribution function is a function of energy $E$ and angular momentum $L$.

$$f_{\text{dehnen}}(E, L) \propto \frac{\Sigma(R_c)}{\sigma^2(R_c)} \exp \left[ \frac{-\Omega(R_c)(L - L_c(E))}{\sigma^2(R_c)} \right].$$

1Available at https://github.com/jobovy/galpy.
where $R$, $L$, and $\Omega(R)$ are the radius, angular momentum, and angular frequency, respectively, of a circular orbit with energy $E$. The gravitational potential is assumed to be a simple power law, given by
\[
\Phi(R) = v_0^2 \times \begin{cases} 
\frac{1}{2\pi} (R/R_0)^2 \beta & \text{for } \beta \neq 0, \\
\ln(R/R_0) & \text{for } \beta = 0,
\end{cases}
\]
(2)
such that the circular velocity is given by
\[
v_c(R) = v_0 (R/R_0)^\beta,
\]
(3)
where $v_0$ is the circular velocity at the Solar circle at radius $R_0$.

To model the bar, we generalize the simple quadrupole bar potential from Dehnen (2000) to a general $\cos(m\phi)$ potential such that
\[
\Phi_b(R, \phi) = A_b(t) \cos(m(\phi_0 - \Omega_b t))
\]
\[
\times \begin{cases} 
-(R/R_0)^p, & \text{for } R \geq R_0, \\
((R/R_0)^p - 2) \times (R_b/R_0)^p, & \text{for } R \leq R_0,
\end{cases}
\]
(4)
where $R_b$ is the bar radius, set to 80 per cent of the corotation radius, $m$ is the integer multiple of the corotation parameter, $\phi_0$ is the angle of the bar with respect to the Sun–Galactic-centre line, and $p$ is the power-law index. To reproduce the Dehnen bar, $m = 2$ and $p = -3$. The bar is grown smoothly following the prescription
\[
A_b(t) = \begin{cases} 
0, & \frac{t}{T_b} < t_1, \\
A_f \left[ \frac{3}{8} \xi^4 - \frac{5}{8} \xi^3 + \frac{15}{16} \xi^2 + \frac{1}{16} \right], & t_1 \leq \frac{t}{T_b} \leq t_1 + t_2, \\
A_f \left[ \frac{t}{T_b} - t_1 \right] > t_1 + t_2,
\end{cases}
\]
(5)
where $t_1$ is the start time of the bar growth (set to half the integration time), and $t_2$ is the duration of the bar growth. $T_b = 2\pi/\Omega_b$ is the period of the bar,
\[
\xi = 2 t/T_b - t_1 - 1,
\]
(6)
and
\[
A_f = \alpha_0 \frac{v_0^2}{3},
\]
(7)
where $\alpha_0$ is the dimensionless ratio of forces owing to the $\cos(m\phi)$ component of the bar potential and the axisymmetric background potential, $\Phi_b$, at Galactocentric radius $R_0$ along the bar’s major axis, corresponding to the amplitude in Fig. 2. Another common method of measuring bar strength is $Q_b$, which is related to $\alpha$ such that
\[
\alpha = Q_b(R_0),
\]
where
\[
Q_b(r) = \frac{\partial \Phi_b}{\partial r}.
\]
(8)

Fig. 3 shows the UV plane in the Solar neighbourhood for the combined TGAS–RAVE data satisfying $\sigma_\pi/\pi \leq 0.1$ and $d < 0.2$ kpc. Four of the moving groups are clearly visible, with Hercules around $(U, \ V) = (-40, -50)$ km s$^{-1}$, Hyades around $(U, \ V) = (-40, -15)$ km s$^{-1}$, Pleiades around $(U, \ V) = (-10, -25)$ km s$^{-1}$, Coma Berenices around $(U, \ V) = (-20, -5)$ km s$^{-1}$, and Sirius around $(U, \ V) = (0, 5)$ km s$^{-1}$, all with respect to the Sun.

Fig. 4 shows the UV plane in the Solar neighbourhood for the simple bar model for a short-fast bar (left) and a long-slow bar (right). For our fast bar model, we set $\alpha_m = \alpha_p = 0.01$, $R_0 = 8.0$ kpc, and $v_0 = 220$ km s$^{-1}$, bar angle of 25$^\circ$ with respect to the Sun–Galactic-centre line and a pattern speed of $\Omega_b = 1.85 \times \Omega_0$ and a half length of $3.5$ kpc. For the slow bar model, we set $\alpha_m = \alpha_p = 0.01$, $R_0 = 8.0$ kpc, and $v_0 = 220$ km s$^{-1}$, a bar angle of 25$^\circ$ with respect to the Sun–Galactic-centre line and a pattern speed of $\Omega_b = 1.3 \times \Omega_0$ and a half length of $5$ kpc. For these simple bar models, the fast bar model creates a strong feature in the UV plane in the region of Hercules, around $U = -30$ km s$^{-1}$ with respect to the LSR, or $U = -40$ km s$^{-1}$ with respect to the Sun, while the slow bar model does not. Note that these models are but a single example of the parameters for a short-fast, and long-slow, bar, and different choices will result in different structure in the UV plane. However, the trend we find is consistent for short-fast rotating bars which have been examined in numerous previous works (e.g. Dehnen 2000; Antoja et al. 2014; Monari et al. 2017c).

For comparison between our models and Solar neighbourhood data, we cross match the Tycho–Gaia Astrometric Solution (TGAS; Michalik, Lindegren & Hobbs 2015) catalogue from the European Space Agency’s Gaia mission (Gaia Collaboration et al. 2016) with data from the Radial Velocity Experiment (RAVE; Steinmetz et al. 2006) to attain six-dimensional phase space information for over 200 000 stars. We perform a simple cut requiring fractional parallax error $\sigma_\pi/\pi \leq 0.1$, and stellar distances of $1/\pi \leq 0.2$ kpc, resulting in a sample of 26 792 stars. Fig. 4 shows the UV plane in the Solar neighbourhood for this sample, uncorrected for the Solar motion. The Hercules stream is clearly visible in the lower left of the figure, around $(U, \ V) = (-40, -50)$ km s$^{-1}$. The Hyades, Pleiades, Coma...
Berenices, and Sirius moving groups are also visible within the main mode.

Note that neither of the simple models presented in Fig. 3 reproduce the complex structure in the main peak of the density in the UV plane (e.g. the other moving groups) shown in Fig. 4. This is unsurprising as this region of $(U, V)$ phase space is heavily influenced by interaction with other non-axisymmetric structure such as the spiral arms (e.g. Quillen 2003; Quillen & Michelin 2005; Sellwood 2010; Michtchenko et al. 2017).

To include an $m = 4$ component of the bar, we add a hexadecapole bar potential. For example, in the multipole expansion of a potential, the hexadecapole component is the fifth (fourth-order) term, whereas the $m = 2$ bar is a simple quadrupole, given by the third (second-order) term of the expansion. We grow this second potential along with the main bar, assuming the same bar length and rotation, and a radial drop-off of $p = -5$. We compare the UV plane in the Solar neighbourhood for a pure $m = 2$ bar against bars with a positive and negative $m = 4$ component, although only a negative $m = 4$ component is observed in the simulations, e.g. the maxima of the $m = 2$ mode aligns with a minima of the $m = 4$ mode.

Fig. 5 shows the UV plane in the Solar neighbourhood for a 5 kpc bar with pattern speed $\Omega_b = 1.3 \times \Omega_0$ to $\Omega_b = 1.425 \times \Omega_0$ from left to right for a purely $m = 2$ bar (upper row), a bar with a negative $m = 4$ component added (centre row) and a bar with a positive $m = 4$ component added (lower row).

The second row of Fig. 5 shows the UV plane in the Solar neighbourhood for a 5 kpc bar comprised of a $m = 2$ component with $\alpha_{m=2} = 0.01$ and a negative $m = 4$ component with $\alpha_{m=4} = -0.0005$. The negative $m = 4$ component clearly creates a new divide in the UV plane, which at higher pattern speeds is close to the observed location of Hercules. However, the bimodality only occurs in the right region to reproduce Hercules at pattern speeds where the OLR feature is also present at high $V$.

The lower row of Fig. 5 shows the UV plane in the Solar neighbourhood for a 5 kpc bar comprised of an $m = 2$ component with $\alpha_{m=2} = 0.01$ and a positive $m = 4$ component with $\alpha_{m=4} = 0.0005$. The positive $m = 4$ component also creates a new divide in the UV plane, but it produces a feature at positive $U$, which is incompatible with being the cause of the Hercules stream.

The amplitude of the $m = 4$ component also has a significant effect on the UV plane. Fig. 6 shows the UV plane in the Solar neighbourhood for a 5 kpc bar with pattern speed $\Omega_b = 1.3\Omega_0$ to $\Omega_b = 1.425\Omega_0$ from left to right for a bar with $\alpha_{m=2} = 0.01$ and $\alpha_{m=4} = -0.0002$ to $-0.0012$ (top to bottom). When comparing the columns the progression of the resonance feature to lower $V$ with a higher pattern speed is clear, and trends as expected (e.g. as shown for the OLR feature in Monari et al. 2017b). When comparing the rows the progressively stronger $m = 4$ component leads to a larger deviation from the rough symmetry around $U = 0$ of a pure $m = 2$ bar. Once we approach $\alpha_{m=4} \approx -0.0008$, the perturbation in the contours of the velocity distribution becomes significantly less smooth, especially for the higher pattern speeds.

We find an amplitude of $\alpha_{m=4} = -0.0005$ to be the best choice to reproduce a Hercules-like feature, without causing a large disruption to the velocity distribution. Fig. 7 shows contours from the long-slow bar model with $\Omega_b = 1.4 \times \Omega_0$, $\alpha_{m=2} = 0.01$, $\alpha_{m=4} = -0.0005$, and a velocity dispersion of $0.13 \times v_0$ overlaid on the TGAS–RAVE UV plane correcting for the Solar motion using the values $U_\odot = -10$ km s$^{-1}$ (Bovy et al. 2012) and

\[ V \sim 30 \text{ km s}^{-1} \text{ arising from resonant trapping by the OLR, which is not seen in the Solar neighbourhood. Both these features are known and explained in more detail in Monari et al. (2017b).} \]
Figure 6. UV plane in the Solar neighbourhood for a 5 kpc bar with pattern speed \( \Omega_b = 1.3 \times \Omega_0 \) to \( \Omega_b = 1.425 \times \Omega_0 \) from left to right for a bar with a negative \( m = 4 \) component with amplitude \( \alpha_m = -0.0002 \) to \(-0.0012 \) top to bottom.

\[ V_\odot = 24 \text{ km s}^{-1} \] (Bovy et al. 2015). For the chosen values of the Solar motion the resonance of the \( m = 4 \) component produces a Hercules-like feature around \((U, V) = (\sim -20, -20) \text{ km s}^{-1}\). However, the high-\( V \) feature arising from the OLR is not observed in the Solar neighbourhood UV plane. We can weaken the OLR feature by reducing the strength of the \( m = 2 \) component of the bar. However, we show here the model with \( \alpha_m = 0.01 \) which is a standard choice for the Dehnen bar model (e.g. Dehnen 2000).

This OLR feature around \( V \sim 30 \text{ km s}^{-1} \) is problematic for a long bar model with \( \Omega_b \gtrsim 1.35 \times \Omega_0 \). Unless some other component of the potential can be shown to suppress this response (e.g. interaction between the bar and spiral resonances) the lack of any observation of a similar feature in the Solar neighbourhood argues against a 5 kpc bar model with \( \Omega_b \gtrsim 1.35 \times \Omega_0 \).

If the Hercules stream originates from the resonance of a bar with an \( m = 4 \) component, then similar kinematics should be observable in four locations around the disc. For example, assuming the Sun lies at \( \phi = 0^\circ \), then the UV plane at \( \phi = 90^\circ, 180^\circ \), and \( 270^\circ \) should contain similar resonance features from the \( m = 4 \) component (it will only be identical at \( \phi = 180^\circ \) owing to the primary \( m = 2 \) mode of the bar). In contrast, if the Hercules stream originates from the \( m = 2 \) short-fast bar model or the \( m = 2 \) component of a long-slow bar, then similar kinematics should only occur at \( \phi = 180^\circ \).

4 FOURFOLD SYMMETRY

If the Hercules stream originates from the resonance of a bar with an \( m = 4 \) component, then similar kinematics should be observable in four locations around the disc. For example, assuming the Sun lies at \( \phi = 0^\circ \), then the UV plane at \( \phi = 90^\circ, 180^\circ \), and \( 270^\circ \) should contain similar resonance features from the \( m = 4 \) component (it will only be identical at \( \phi = 180^\circ \) owing to the primary \( m = 2 \) mode of the bar). In contrast, if the Hercules stream originates from the \( m = 2 \) short-fast bar model or the \( m = 2 \) component of a long-slow bar, then similar kinematics should only occur at \( \phi = 180^\circ \).
Bovy (2010) made a prediction across the disc for the Hercules stream if it originates from the short-fast bar model. Here, we make the same prediction around the $R_0 = 8\, \text{kpc}$ circle for the long-slow bar with only an $m = 2$ component with $\Omega_b = 1.3 \times \Omega_0$, and one which includes an $m = 4$ component with $\Omega_b = 1.4 \times \Omega_0$ as shown in Fig. 7.

Fig. 8 shows the $UV$ plane along the Solar circle ($R = 8\, \text{kpc}$) at varying azimuths by column for the short bar model from Hunt et al. (2018) (top row), the $m = 2$ component long-slow bar model (centre row) where it is proposed that the Hercules can originate from trapping around the CR, and the $m = 4$ long bar model from Fig. 7 (bottom row) where it is proposed that Hercules can originate from the 4:1 OLR.

The top row of Fig. 8 shows the $UV$ plane for an example short bar model. It displays twofold symmetry, e.g. the $UV$ plane at 0 and $\pi$ rad is identical. The second row of Fig. 8 shows that the $UV$ plane of a standard Dehnen bar with $\alpha_{m = 2} = 0.01$ and $\Omega_b = 1.3 \times \Omega_0$ also displays twofold symmetry. The third row of Fig. 8 shows the $UV$ plane for a 5 kpc bar with $\alpha_{m = 2} = 0.01$, $\alpha_{m = 4} = -0.0005$, and $\Omega_b = 1.425 \times \Omega_0$. This bar model shows a mix of twofold and fourfold symmetries. The OLR feature at high $V$ which originates from the $m = 2$ component is twofold symmetric, such that it repeats every $\pi/2$ rad. However, the feature around the area of Hercules arising from the $m = 4$ component is fourfold symmetric, such that it repeats every $\pi/2$ rad, visible at $\phi = 0$, $\pi/2$, and $\pi$ rad.

In the near future data release 2 (DR2; Katz & Brown 2017) from the European Space Agency’s Gaia mission (Gaia Collaboration et al. 2016) will provide detailed positions and proper motions for over $1.3 \times 10^6$ stars, and radial velocities for over $6 \times 10^4$ stars. This will allow us to explore kinematics away from the Solar neighbourhood and search for twofold or fourfold symmetric features. We will not be able to examine the $UV$ plane across the disc specifically with DR2 owing to the lower number of radial velocities, but similar to the line-of-sight identified in Bovy (2010) which showed a strong signature of Hercules, there will exist lines of sight for which the gaps in the velocity distribution owing to various resonances are visible in the proper motion data alone.

For that reason, we do not make a detailed prediction of the model parameters, but merely highlight another potential mechanism for the creation of the Hercules stream in a model with a long-slow bar which can be tested against the data from Gaia and other Galactic surveys.

5 DISCUSSION AND OUTLOOK

In this work, we have shown that it is possible to create a Hercules-like feature in the Solar neighbourhood $UV$ plane in a model with a 5 kpc bar, containing both an $m = 2$ and $m = 4$ Fourier components. The other moving groups present in the main mode of the velocity distribution are not reproduced, likely because they originate from spiral resonances (e.g. Quillen & Michelin 2005; Sellwood 2010), or interaction between the bar and spiral resonances (e.g. Quillen 2003; Monari et al. 2016). We will investigate this further in an upcoming work.

Although existing long bar models have been able to reproduce a Hercules-like feature through resonant trapping around the corotation radius (Monari et al. 2017a; Pérez-Villegas et al. 2017), the effect is weaker than observed in the data, either providing no clear separation between the modes, or providing only a weak perturbation to the contours of the $UV$ plane. We are not suggesting that the parametrization of this model is a perfect representation of the bar, considering the OLR feature present at high $V$, but merely that a resonance origin for Hercules is compatible with the 4:1 OLR of a long bar model, providing a more complex potential is used.

We make a general prediction of fourfold symmetry across the Galactic disc if Hercules is caused by the $m = 4$ component of the bar. At this stage, we lack sufficient data to fully trace the stream to larger distances. However, in the near future Gaia DR2 will provide detailed five-dimensional phase space information for over $1.5 \times 10^6$ stars down to $\sim 20$ mag, allowing us to trace the Hercules stream and its velocity for many kpc across the Galactic disc. This will enable us to make detailed comparisons with the competing models, and help explain the origins of the kinematic features in the Solar neighbourhood.

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Figure 8. $UV$ plane along the Solar circle ($R = 8$ kpc) at varying azimuths by column for the short bar (top row), $m = 2$ component long-slow bar (centre row), and the $m = 4$ long-slow bar model from Fig. 7 (bottom row).

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