The properties of the local spiral arms from RAVE data

Siebert, A.; Famaey, B.; Binney, J.; Burnett, B.; Faure, C.; Minchev, I.; Williams, M. E. K.; Bienayme, O.; Bland-Hawthorn, J.; Boeche, C.

Published in: Monthly Notices of the Royal Astronomical Society

DOI: 10.1111/j.1365-2966.2012.21638.x

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date: 2012

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
The properties of the local spiral arms from RAVE data: two-dimensional density wave approach

A. Siebert,1⋆ B. Famaey,1 J. Binney,2 B. Burnett,2 C. Faure,1 I. Minchev,3 M. E. K. Williams,3 O. Bienaymé,1 J. Bland-Hawthorn,4 C. Boeche,5 B. K. Gibson,6,7 E. K. Grebel,5 A. Helmi,8 A. Just,5 U. Munari,9 J. F. Navarro,10 Q. A. Parker,11,12,13 W. A. Reid,11,12 G. Seabroke,14 A. Siviero,3,15 M. Steinmetz3 and T. Zwitter16,17

1Observatoire Astronomique, Université de Strasbourg, CNRS, 11 rue de l’université, 67000 Strasbourg, France
2Rudolf Peierls Centre for Theoretical Physics, 1 Keble Road, Oxford OX1 3NP
3Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany
4Sydney Institute for Astronomy, University of Sydney, Sydney, NSW 2006, Australia
5Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany
6Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE
7Department of Astronomy and Physics, Saint Mary’s University, Halifax, Nova Scotia B3H 3C3, Canada
8Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, the Netherlands
9INAF Astronomical Observatory of Padova, 36012 Asiago (VI), Italy
10Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada
11Department of Physics and Astronomy, Macquuary University, NSW 2109, Sydney, Australia
12Macquarie Research Centre for Astronomy, Astrophysics and Astrophotonics, NSW 2109, Sydney, Australia
13Australian Astronomical Observatory, PO Box 296, Epping, NSW 2121, Australia
14Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking RH5 6NT
15Department of Physics and Astronomy ‘G.Galilei’, Padova University, Vicolo dell’Osservatorio 2, Padova 35122, Italy
16Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, SI-1000 Ljubljana, Slovenia
17Center of Excellence SPACE-SI, Askerceva cesta 12, SI-1000 Ljubljana, Slovenia

Accepted 2012 July 2. Received 2012 July 2; in original form 2012 April 12

ABSTRACT

Using the Radial Velocity Experiment (RAVE) survey, we recently brought to light a gradient in the mean galactocentric radial velocity of stars in the extended solar neighbourhood. This gradient likely originates from non-axisymmetric perturbations of the potential, among which a perturbation by spiral arms is a possible explanation. Here, we apply the traditional density wave theory and analytically model the radial component of the two-dimensional velocity field. Provided that the radial velocity gradient is caused by relatively long-lived spiral arms that can affect stars substantially above the plane, this analytic model provides new independent estimates for the parameters of the Milky Way spiral structure. Our analysis favours a two-armed perturbation with the Sun close to the inner ultra-harmonic 4:1 resonance, with a pattern speed \( \Omega_0 = 18.6^{+0.3}_{-0.2} \) km s\(^{-1}\) kpc\(^{-1}\) and a small amplitude \( A = 0.55^{+0.02}_{-0.02} \) per cent of the background potential (14 per cent of the background density). This model can serve as a basis for numerical simulations in three dimensions, additionally including a possible influence of the Galactic bar and/or other non-axisymmetric modes.

Key words: stars: kinematics and dynamics – Galaxy: fundamental parameters – Galaxy: kinematics and dynamics.

1 INTRODUCTION

It has long been recognized that internal secular evolution processes should play a major role in shaping galaxy discs. Among

the main drivers of this secular evolution are the disc instabilities and associated non-axisymmetric perturbations, including the bar and spiral arms. Questions about their nature, transient or quasi-stationary (e.g. Sellwood 2010a; Quillen et al. 2011; Grand, Kawata & Cropper 2012a), about their detailed structure and dynamics such as their amplitude, pattern speed, pitch angle or number of arms, as well as questions about their detailed influence on secular
processes like stellar migration (Sellwood & Binney 2002; Minchev & Famaey 2010), are all essential elements for a better understanding of galactic evolution. The Milky Way provides a unique laboratory in which a snapshot of the dynamical effect of present-day disc non-axisymmetries can be studied in great detail, and help answering the above questions.

Current knowledge of the structure and dynamics of the bar and the spiral arms of the Milky Way relies both on the gas and, notably, on its observed longitude–velocity diagram (Binney et al. 1991; Bissantz, Englmaier & Gerhard 2003; Englmaier, Pohl & Bissantz 2011) or masers in high-mass star-forming regions (Reid et al. 2009, and references therein), and on the stars (e.g. Georgelin & Georgelin 1976; Binney, Gerhard & Spergel 1997; Stanek et al. 1997; Benjamin et al. 2005; Lépine et al. 2011b). For the spiral arms, both types of constraints are combined in a recent study by Vallée (2008), whose model predicts the location in space and velocity for the spiral arms.

With the advent of new spectroscopic and astrometric surveys, six-dimensional phase-space information for stars in an increasingly large volume around the Sun allows us to set new dynamical constraints on the non-axisymmetric perturbations of the Galactic potential. An example of such new detailed kinematical information on stellar motions in the extended solar neighbourhood is the recently detected (galactocentric) radial velocity gradient of \( \sim 4 \, \text{km s}^{-1} \text{kpc}^{-1} \) by Siebert et al. (2011a), making use of more than 200 thousand stars from the Radial Velocity Experiment (RAVE) survey. If this result is not owing to systematic distance errors (which the geometry of the radial velocity flow seems to exclude by not depending on distance and longitude in any systematically biased way), and more importantly, if one assumes that, at first order, what is seen above the plane is a reflection of what would happen in a razor-thin disc, and that the spiral arms are long-lived, one can apply the analytic density wave description of spiral arms proposed by Lin & Shu (1964) to constrain the shape, amplitude and dynamics of spiral arms.

Whether long-lived density waves are the correct description of spiral patterns in galaxies remains heavily debated. From a theoretical point of view, while it seems that the radial velocity dispersion profile needed to support long-lived spiral waves in barless discs (e.g. Bertin & Lin 1996) would be heavily unstable (Sellwood 2010a), the situation is much less clear in the presence of a central bar, where non-linear mode coupling between the bar and spiral could sustain a long-lived spiral pattern (Voglis, Stavropoulos & Kalapotharakos 2006; Salo et al. 2010; Quillen et al. 2011; Minchev et al. 2012), while Grand, Kawata & Cropper (2012b), however, find that spiral arms are transient even in the presence of a central bar. On the other hand, D’Onghia et al. (2012) find locally long-lived self-perpetuating spiral arms which could be locally consistent with density waves, but fluctuating in amplitude with time. Furthermore, long-lived spirals can also develop as being sustained by coherent oscillations due to a flyby galaxy encounter (Struck, Dobbs & Hwang 2011), a process we know to be ongoing for the Milky Way, and cosmologically simulated disc galaxies exhibit a distribution of young stars consistent with the predictions of classical density wave theory for long-lived spirals (Pilkinson, Gibson & Jones 2012). Finally, let us note that both long-lived and transient spirals can coexist in a galaxy, which adds complexity to the picture.

On the observational side the situation is also unclear. Evidence seems to exist for both transient and long-lived spiral arms: e.g. M81 apparently contains long-lived spiral arms consistent with the classical density wave theory (Lowe et al. 1994; Adler & Weisstpfahl 1996; Kendall et al. 2008) while in M51, even if its disc stream-


gradient of disc stars in the fourth quadrant, directed radially from the Galactic Centre (Siebert et al. 2011a). The two-dimensional
mean galactocentric radial velocity field in the Galactic plane is presented in Fig. 1 where we use a box \(4 \times 4\) kpc in size, centred on the Sun, sampled using 60 bins in each direction. For this analysis, we restrict ourselves to bins containing more than five stars and the mean velocity is computed using a median function. Note that converting velocities in the heliocentric reference frame into the \((V_R, V_\theta)\) galactocentric coordinates requires the galactocentric radius of the Sun \(R_0\), the Sun’s peculiar velocity \(v_\odot\) with respect to the Local Standard of Rest (LSR) and the motion of the LSR with respect to the Galactic Centre \(V_{1,LSR}\). We assume \(R_0 = 8\) kpc for the distance of the Sun to the Galactic Centre and \(V_{1,LSR} = 220\) km s\(^{-1}\) to match the values used for the mass model (see Section 2.2). We use the latest determination of the value of the solar motion by Schönrich, Binney & Dehnen (2010): \((U_\odot, V_\odot) = (11.1, 12.24)\) km s\(^{-1}\).

The gradient affects a sample dominated at large distances by red giants, with a typical velocity dispersion \(\sigma_R \sim 30–40\) km s\(^{-1}\), and affects stars substantially above the plane, keeping in mind that RAVE lines of sight are typically at \(|b| \sim 20^\circ\). The zone where the gradient is the steepest is populated with stars with typically \(|z| \sim 500\) pc. However, if \(U_{LSR}\) is positive (a local mean motion towards the inner Galaxy), then \(V_R\) would be by construction negative in the Sun’s neighbourhood and reach 0 at larger distances and larger heights. In the modelling procedure hereafter, we let \((V_R)_0 \equiv -U_{LSR}\) be a parameter of the model to allow us to account for uncertainties on this quantity.

Ideally, one would also use the tangential velocity field \(\langle V_\theta \rangle\) in combination with the \(\langle V_R \rangle\) field. However, as stated above, our sample reaches distances to the Galactic plane of 1 kpc, avoiding the regions close to the plane. The RAVE survey mimicking a magnitude limited survey in fields 6° in diameter on the sky, each field containing a different number of stars, the stellar population mixture varies from point to point on the maps. Therefore, the contribution of the asymmetric drift is difficult to estimate while it enters the calculation of the \(V_\theta\) component. Hence, we chose to restrict our analysis to the \(\langle V_R \rangle\) field, although we give the full set of equations, including this component, in the next section.

2.2 Density wave model

To model the velocity field, we use the density wave description of spiral arms proposed by Lin & Shu (1964) and further developed in Lin, Yuan & Shu (1969) and Shu, Stachnik & Yost (1971). This model is based on an asymptotic analysis of the WKB type of the Euler/Boltzmann equations, valid only in the regime of weak, long-lived and tightly wound spirals (small pitch angle). This model being well known and documented (see e.g. Binney & Tremaine 2008), we restrict its description to the main results used in this study.

The perturbation to the potential considered is of the form

\[
\Phi_1 = A(R) \exp[i(\nu t - m\theta + \Phi(R))],
\]

where \(A(R)\) is the amplitude of the perturbation, \(m\) is the number of arms and \(\Phi(R)\) is a monotonic function. The perturbation rotates at an angular frequency given by

\[
\Omega_c = \omega/m.
\]

The perturbations in the components of the mean velocities \(\langle V_R \rangle\) and \(\langle V_\theta \rangle\), where \((R, \theta)\) are the coordinates in the cylindrical coordinate system centred on the Galaxy, are given by

\[
\langle V_R \rangle = kA \frac{v}{\kappa} \frac{1}{1 - \nu^2} F^{(1)}(x) \cos(\chi)
\]

\[
\langle V_\theta \rangle = -kA \frac{1}{2} \frac{1}{\Omega} \frac{1}{1 - \nu^2} F^{(2)}(x) \sin(\chi)
\]

where

\[
x = \frac{k^2 \sigma_R^2}{\kappa^2},
\]

\(k\) being the radial wavenumber, \(\sigma_R\) is the velocity dispersion, \(\kappa\) is the epicyclic frequency and \(\nu\) is defined by \(\nu = \Omega - \Omega_c/\kappa\).

The functions \(F^{(1)}\) and \(F^{(2)}\) are the ‘reduction factors’ that correct the mean velocities for the effect of velocity dispersion, lowering the effect of the spiral perturbation on the velocity field as the velocity dispersion increases. In the limit of a zero velocity dispersion \((c^{(1)} = c^{(2)} = 1)\) we recover the velocity field of the gas while if \(\sigma_R\) becomes large, \(c^{(1)} = c^{(2)} \rightarrow 0\) and the velocity field becomes

\[
(c^{(1)} = c^{(2)} = 1) \text{ we recover the velocity field of the gas while if } \sigma_R \text{ becomes large, } c^{(1)} = c^{(2)} \rightarrow 0 \text{ and the velocity field becomes}
\]
unaffected by the spiral perturbation. The two functions are given in appendix B of Lin et al. (1969).

The phase of the spiral pattern \( \chi \) is defined by

\[
\chi = \cot \theta + \Phi(R) \tag{5}
\]

which, in the case of logarithmic spirals with \( \Phi(R) = m \cot \iota \ln R \) in equation (1) (\( \iota \) being the pitch angle), can be written in a more convenient form as

\[
\chi = \chi_0 + m(\cot \iota \ln(R/R_0) - (\theta - \theta_0)) \tag{6}
\]

The subscripts 0 in the previous equation refer to the value at the Sun’s location. The radial wavenumber \( k \) is then given by

\[
k(R) = \Phi'(R) = m \cot \iota / R, \tag{7}
\]

with \( k(R) < 0 \) for trailing waves and \( k(R) > 0 \) for leading waves.

The mean velocities of equation (3) vary in the Galactic plane as a function of \( R \) and \( \theta \), the modulation depending on the mass model via \( \Omega \) and \( \kappa \), the velocity dispersion in the radial direction \( \sigma_R \) via the reduction factors and on the parameters of the spiral perturbation. These parameters are the number of arms \( m \), the amplitude of the perturbation \( A \), its pattern speed \( \Omega_0 \), the pitch angle \( \iota \) and the phase \( \chi_0 \). In addition we chose to include \((V_R)_0\) as a free parameter while computing the model to account for possible uncertainties on \( U_{\text{LSR}} \).

While this parameter is usually taken into account while computing the halo dominates the rotation curve (model I and II, respectively). The two quantities such as the Oort constants, the surface mass density within 1.1 kpc or the total mass within 100 kpc of the Milky Way. The two models correspond to two limiting cases where either the disc or \( 1.1 \) kpc or the total mass within 100 kpc of the Milky Way. The two models correspond to two limiting cases where either the disc or.

The mean velocities of equation (3) are compared to the two-dimensional velocity field of Section 2.1. The comparison is done using a chi-square estimator

\[
\chi^2 = \sum_i \frac{(V_R)_i, \text{obs} - (V_R)_i, \text{model})^2}{\sigma_i, \text{obs}^2}, \tag{8}
\]

where the sum is on all bins containing at least five stars and \( \sigma_i, \text{obs} \) is the error on the mean velocity shown in Fig. 1 (right-hand panel). We restrict the analysis to the mean velocity in the radial direction, the tangential velocities being affected by the asymmetric drift which cannot be properly taken into account in the model, our sample being a mixture of stellar populations of different ages, even though it is dominated by the old thin disc (see Section 2.1).

The summary of the chi-square analysis is presented in Table 1 and the chi-square contours for the best models are presented in Fig. 2. In this figure, the two panels show the \( 1 \sigma \), \( 2 \sigma \) and \( 3 \sigma \) contours, fixing all the other parameters to the best-fitting solution, in the \( \Omega_0 \) versus amplitude plane (left-hand panel) and pitch angle \( \iota \) versus phase \( \chi_0 \) (right-hand panel). The plain lines are for the mass model I, and the red dashed lines are for model II.

The best-fitting model is obtained for a two-armed spiral mode with the mass model II. The best-fitting solution for model I is \( \chi_0 \) (right-hand panel). We note that our sample reaches only 2 kpc away from the Sun, not deep enough in the plane to disentangle the effect of a radial motion of the LSR from uncertainties in the \( U_0 \) component of the solar motion with respect to the LSR. Therefore, we should keep in mind that a non-null best-fitting value of the \((V_R)_0\) parameter does not necessarily imply a radial motion of the LSR.

1 Recall that \( U_{\text{LSR}} = -(V_R)_0 \).
The local spiral structure with RAVE

Table 1. Chi-square results. Parameters with error bars were kept free in the minimization. The error bars correspond to the $1\sigma$ internal errors obtained from the chi-square contour. Models marked with an asterisk (*) have a large pitch angle (open arms) and do not satisfy the tight-winding approximation. The number of pixels used in the minimization procedure is 1595.

<table>
<thead>
<tr>
<th>Mass model</th>
<th>$m$</th>
<th>$(V_k)_{R_0}$ km s$^{-1}$</th>
<th>$\Omega_\rho$ km s$^{-1}$ kpc$^{-1}$</th>
<th>$A$ per cent (total, disc)</th>
<th>$i$ (o)</th>
<th>$\chi_0$ (o)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2</td>
<td>0.9$^{+0.3}_{-0.2}$</td>
<td>18.9$^{+0.3}_{-0.2}$</td>
<td>0.50$^{+0.02}_{-0.02}$</td>
<td>2.27$^{+0.08}_{-0.07}$</td>
<td>$-10.9^{+0.3}_{-0.4}$</td>
<td>76.9$^{+1.1}_{-1.2}$</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>-5</td>
<td>16.1$^{+0.3}_{-0.2}$</td>
<td>0.78$^{+0.01}_{-0.01}$</td>
<td>3.50$^{+0.07}_{-0.06}$</td>
<td>$-23.2^{+0.3}_{-0.5}$</td>
<td>57.3$^{+0.6}_{-0.5}$</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>0</td>
<td>18.8$^{+0.2}_{-0.3}$</td>
<td>0.49$^{+0.02}_{-0.02}$</td>
<td>2.21$^{+0.08}_{-0.09}$</td>
<td>$-9.1^{+0.3}_{-0.4}$</td>
<td>65.8$^{+1.5}_{-1.0}$</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>5</td>
<td>19.3$^{+0.1}_{-0.2}$</td>
<td>0.69$^{+0.02}_{-0.01}$</td>
<td>3.19$^{+0.09}_{-0.05}$</td>
<td>$-15.6^{+0.7}_{-0.6}$</td>
<td>112.1$^{+1.0}_{-0.9}$</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>0.9$^{+0.3}_{-0.2}$</td>
<td>18.6$^{+0.3}_{-0.2}$</td>
<td>0.55$^{+0.02}_{-0.02}$</td>
<td>3.09$^{+0.10}_{-0.13}$</td>
<td>$-10.0^{+0.4}_{-0.4}$</td>
<td>76.0$^{+1.3}_{-1.0}$</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>-5</td>
<td>15.1$^{+0.1}_{-0.1}$</td>
<td>0.71$^{+0.01}_{-0.01}$</td>
<td>3.93$^{+0.06}_{-0.07}$</td>
<td>$-22.3^{+0.6}_{-0.6}$</td>
<td>55.7$^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>0</td>
<td>18.5$^{+0.2}_{-0.3}$</td>
<td>0.54$^{+0.02}_{-0.03}$</td>
<td>3.03$^{+0.15}_{-0.15}$</td>
<td>$-9.3^{+0.4}_{-0.3}$</td>
<td>66.6$^{+1.1}_{-1.0}$</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>5</td>
<td>16.8$^{+0.1}_{-0.1}$</td>
<td>0.51$^{+0.01}_{-0.01}$</td>
<td>2.84$^{+0.07}_{-0.05}$</td>
<td>$-16.3^{+0.7}_{-0.6}$</td>
<td>113.1$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>I</td>
<td>4</td>
<td>4.9$^{+0.1}_{-0.1}$</td>
<td>25.8$^{+0.1}_{-0.1}$</td>
<td>0.71$^{+0.02}_{-0.01}$</td>
<td>3.22$^{+0.08}_{-0.06}$</td>
<td>$-26.0^{+0.6}_{-0.5}$</td>
<td>132.8$^{+1.8}_{-1.7}$</td>
</tr>
<tr>
<td>II</td>
<td>4</td>
<td>4.9$^{+0.1}_{-0.1}$</td>
<td>25.9$^{+0.1}_{-0.1}$</td>
<td>0.91$^{+0.03}_{-0.02}$</td>
<td>5.00$^{+0.16}_{-0.09}$</td>
<td>$-26.7^{+1.0}_{-0.4}$</td>
<td>135.0$^{+2.3}_{-1.7}$</td>
</tr>
</tbody>
</table>

Figure 2. Cuts through the chi-square space around the best-fitting models in the amplitude versus pattern speed plane (left-hand panel) and phase versus pitch angle plane (right-hand panel). The crosses mark the location of the best fit while the contours are the $1\sigma$, $2\sigma$ and $3\sigma$ limits. The amplitude in the left-hand panel is given as a percentage of the background potential at the Sun’s location. The plain lines are for the mass model I and the dashed lines for the mass model II. In both panels the top contours are for $m = 4$, and the bottom contours for $m = 2$.

The chi-square value of the best $m = 4$ solution is also close to the best $m = 2$ solution. However, for $m = 4$ the pitch angle $i$ is found to be $\approx -26^\circ$, out of the bounds of the tight-winding approximation upon which the density wave model relies ($\max(|i|) \approx 15^\circ - 20^\circ$; Lin et al. 1969). Hence, for a four-armed pattern, we conclude that no satisfactory solution is found and we will discard four-armed patterns in the following discussion.

Focusing on the $m = 2$ mode, a strong correlation is observed between the amplitude and the pattern speed while the correlation is weaker between the pitch angle and the phase (Fig. 2). If the phase and pitch angle are well determined, the shape of the contours in amplitude versus $\Omega_\rho$ indicates a large range in possible solutions at the $3\sigma$ level: $\Omega_\rho$ varies from 12 to 22 km s$^{-1}$ kpc$^{-1}$ and the amplitude from 0.1 to 0.9 per cent of the background potential. The amplitude of the best-fitting model is $A \approx 0.55$ per cent of the background potential. This value translates to 14 per cent of the background density which is close to the value proposed by Minchev & Famaey (2010) and consistent with earlier determinations summarized in Antoja et al. (2011) for the local spiral amplitude. We also note that corotating waves ($\Omega_\rho \sim 27.5$ km s$^{-1}$ kpc$^{-1}$) seem to be excluded.

Finally, among the $m = 2$ solutions, a low radial component of the LSR velocity is preferred. The best-fitting model converges to $(V_k)_{R_0} = 0.9$ km s$^{-1}$ while a zero radial component cannot be ruled out when comparing the chi-square values. On the other hand, a more pronounced outwards motion of the LSR ( $(V_k)_{R_0} = 5$ km s$^{-1}$ ) shows significantly larger chi-square values while an inwards motion of $-5$ km s$^{-1}$ as suggested by Smith et al. (2012) is even less consistent. However in the latter case, the model converges outside of the range of allowed values for the pitch angle which limits the conclusions one can draw from this result. We note that our
best-fitting value is consistent with the Schönrich et al. (2010) errors at the 2σ level when considering the error bars on the determination of $U$ (e.g. $U = 11.1^{+0.69}_{-0.75}$ km s$^{-1}$). In the next section, we will concentrate on the best $m = 2$ models and their implications for the structure of the Galactic disc.

### 3.2 Resonances and spiral structure

The best-fitting $\langle V_R \rangle$ velocity fields for the $m = 2$ solutions using the mass models II is presented in Fig. 3. Although both reproduce equally well the structure of the velocity field between $y = \pm 1$ kpc, a small difference between the two solutions exists, model I predicting larger velocities in the top right and lower left corners of our sample (bottom-right panel). However the velocity difference reaches only 0.2 km s$^{-1}$, a level that lies below the capabilities of our data. The region below $y = -1$ km s$^{-1}$ and at $0 < x < 1$ km s$^{-1}$ is apparently poorly reproduced; however the lower-left panel of Fig. 3 indicates that our solution stays well within the observational errors. The right-hand panel of Fig. 1 indicates that this region suffers from large velocity errors and has therefore a lower weight in the solution. In the regions where our data are of the best quality (mostly $|y| < 1$ kpc), our models reproduce adequately the observed velocity field.

Focusing on the pattern speed, our best models suggest that the Sun is located $\sim 200$ pc inside the inner 4:1 resonance (ultra-harmonic resonance or UHR) of the spiral pattern (Fig. 4). Our finding for the pattern speed $\Omega_p = 18 - 19$ km s$^{-1}$ kpc$^{-1}$ is in agreement with recent studies that also place the Sun close to the UHR: $\Omega_p = 17$ km s$^{-1}$ kpc$^{-1}$ by Antoja et al. (2011), $\Omega_p = 18$ km s$^{-1}$ kpc$^{-1}$ by Quillen & Minchev (2005) or $\Omega_p/\Omega_0 = 0.65$ by Pompeia et al. (2011) to be compared to $\Omega_p/\Omega_0 \sim 0.68$ in our study. However, as shown by Gerhard (2011), determinations of the spiral arms’ pattern speed range from 17 to 28 km s$^{-1}$ kpc$^{-1}$, the higher values being preferred by open cluster birthplaces while hydrodynamical simulations and phase space substructures favour slower pattern speeds. It is interesting to note that the pattern speeds found from velocity space substructures (Quillen & Minchev 2005; Antoja et al. 2011; Pompeia et al. 2011) are close to our value. This would indicate a similar origin for the velocity gradient and the velocity substructures, reinforcing our assumption that the velocity gradient we observed is due to spiral arms. However this statement must be put in perspective as both types of study rely on the same assumptions that the spiral pattern is long-lived and tightly wound.

Comparing the predicted density pattern to the location of the spiral arms obtained by Englmaier et al. (2011) in the gas,
we find a good agreement (Fig. 4, right-hand panel). Both the Perseus arm and the Centaurus arm are recovered at the proper location. The Sagittarius–Carina arm is not recovered in our models. This indicates that this feature is not a dominant feature in the Solar neighbourhood, reinforcing the view that the Milky Way spiral arm pattern is dominated by two main arms, Perseus and Centaurus (Drimmel 2000; Drimmel & Spergel 2001; Benjamin et al. 2005; Churchwell et al. 2009). Contrary to the \( m = 2 \) models, our best-fitting \( m = 4 \) solution does not reproduce any of the known spiral arms, in addition to being invalidated by its large pitch angle, hence an \( m = 2 \) mode for the spiral pattern in the Milky Way is preferred within the Lin–Shu regime.

4 CONCLUSION

We have analysed the velocity gradient detected by Siebert et al. (2011a) using the RAVE data in the framework of the density wave model of Lin & Shu (1964), assuming that the velocity gradient we detected is due only to spiral arms and that the spiral arms in the Milky Way are long-lived.

Our model converges properly for an \( m = 2 \) pattern, while if the chi-square of the \( m = 4 \) solutions are comparable, the predicted pitch angle is too large, invalidating the solution.

The best-fitting solutions for \( m = 2 \) adequately reproduce the observed velocity field for \( \langle V_R \rangle \) in the region \( |y| < 1 \text{kpc} \) where our data are the most reliable. Outside of this region, the difference between the model and the observations is still within the observational errors although the agreement is less clear.

The predicted pattern speed places the Sun about 200 pc outside the inner UHR of the spiral arms. Such a location of the Sun is consistent with previous works based on velocity space substructures, suggesting a similar origin for the velocity space substructures and the \( \langle V_R \rangle \) gradient. Our best-fitting value for the amplitude of the spiral perturbation, \( A = 0.55_{-0.02}^{+0.02} \) per cent of the background potential or 14 per cent of the background density, is consistent with the value proposed by e.g. Minchev & Famaey (2010) and is also in the range of earlier measurements as summarized in Antoja et al. (2011).

Comparing our model to the location of spiral arms in the gas, we find a good agreement with the location of the major spiral arms given by Englmaier et al. (2011). The density enhancement predicted by our best model matches the location of the Perseus and Centaurus arms. The Sagittarius arm is not reproduced by our solution which tends to reinforce previous studies concluding that the Milky Way spiral potential is dominated by a two-armed mode, the Sagittarius–Carina arm being a minor feature for the dynamics of the disc.

Our study relies on the density wave model of Lin & Shu (1964) and we assumed no vertical variation of the \( \langle V_R \rangle \) field within the limit of our data. RAVE data do contain the three-dimensional spatial information which we will use in further studies. However, going from 2D to 3D requires an upgrade of our modelling technique taking properly into account the asymmetric drift and the vertical variation of the spiral potential. Moreover, vertical perturbations leading to possible variations of \( \langle V_R \rangle \) at \( (R, z) \) (Smith et al. 2012; Widrow et al. 2012; Williams et al., in preparation) are intrinsically not taken into account in our analysis. Future 3D simulations of such perturbations and their possible influence on the \( \langle V_R \rangle \) field will be necessary to disentangle their possible effects from the velocity gradient modelled here. Finally we note that our model is local as a result of the tight-winding approximation (see e.g. discussion in Binney 2012, section 1.4.2). Ongoing surveys like Gaia-ESO

Figure 4. Left: circular frequency as a function of galactocentric distance for the mass model I of Binney & Tremaine (thick lines). The dotted and dashed lines are, respectively, the relations \( \Omega \pm \pi/4 \) and \( \Omega \pm \pi/2 \) versus \( R \). The location of the Sun is marked by the vertical dotted line at \( R_0 = 8 \text{kpc} \). The horizontal lines are the pattern speed corresponding to the best-fitting models for \( m = 2 \) (plain lines) and \( m = 4 \) (dash–dotted lines). Right: density associated with the spiral perturbation. The contours are evenly spaced by 0.1 \( \sigma_0 \), the background column density, from 0.1 to 0.5\( \sigma_0 \). The blue contour depicts the footprint of the RAVE data. The red lines mark the location of the spiral arms in the gas from Englmaier et al. (2011). From left to right we have Cygnus arm (top-left corner), the Perseus arm, the Sagittarius–Carina arm and the Scutum–Centaurus arm. The results for the mass model II are almost identical and are therefore not presented.
(GES) or SDSS/SEGUE will provide data in the Galactic plane that can be used to test our models further in towards the Galactic Centre (GES) or further out (SDSS/SEGUE). It will be interesting to test whether these two surveys predict the same pattern speed for the spiral arms.

ACKNOWLEDGMENTS

Funding for RAVE has been provided by: the Australian Astronomical Observatory; the Leibniz-Institut fuer Astrophysik Potsdam (AIP); the Australian National University; the Australian Research Council; the French National Research Agency; the German Research Foundation (SPP 1177 and SFB 881); the European Research Council (ERC-StG 240271 Galactica); the Istituto Nazionale di Astrofisica at Padova; The Johns Hopkins University; the National Science Foundation of the USA (AST-0908326); the W. M. Keck foundation; the Macquarie University; the Netherlands Research School for Astronomy; the Natural Sciences and Engineering Research Council of Canada; the Slovenian Research Agency; the Swiss National Science Foundation; the Science & Technology Facilities Council of the UK; Opticon; Strasbourg Observatory; and the Universities of Groningen, Heidelberg and Sydney. The RAVE website is: http://www.rave-survey.org.

REFERENCES

Burnett B. et al., 2011, A&A, 532, A113
Churchwell E. et al., 2009, PASP, 121, 213
Englmaier P., Pohl M., Bissantz N., 2011, Memorie della Societa Astronomica Italiana Suppl., 18, 199
Gerhard O., 2011, Memorie della Societa Astronomica Italiana Suppl., 18, 185
Quillen A. C., Minchev I., 2005, AJ, 130, 576
Siebert A. et al., 2011b, AJ, 141, 187

This paper has been typeset from a TeX/LaTeX file prepared by the author.