The Galactic Disc in Action Space as seen by Gaia DR2

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The quality and quantity of 6D stellar position-velocity measurements in the second Gaia data release (DR2) allows to study small-scale structure in the orbit distribution of the Galactic disc beyond the immediate Solar neighborhood. We investigate the distribution of orbital actions \((J_R, J_\phi = L_z, J_z)\) of \(\sim 3.5\) million stars within 1.5 kpc of the Sun, for which precise actions can be calculated from Gaia DR2 alone. This distribution \(n(J_R, L_z)\) reveals a remarkable amount of sub-structure. The known moving groups in the \((U,V)\)-plane of the Solar neighborhood correspond to overdensities in \((J_R, L_z)\), as expected. But \(n(J_R, L_z)\) also exhibits a wealth of density clumps and ridges that extend towards higher \(J_R\). These \(n(J_R, L_z)\) features are most prominent among orbits that stay close to the Galactic plane and remain consistently visible out to \(\sim 1.5\) kpc, as opposed to the sub-structure in velocity space. Some of these \(n(J_R, L_z)\) ridges resemble features expected from rapid orbit diffusion along particular \((J_R, L_z)\)-directions in the presence of various resonances. Several of these \(n(J_R, L_z)\) structures show a dramatic imbalance of stars moving in or out, suggesting that stars are not phase-mixed along orbits or on resonant orbits. Orbital action and angle space of stars in Gaia DR2 is therefore highly structured over kpc-scales, and appears to be very informative for modeling studies of non-axisymmetric structure and resonances in the Galactic disc.

Key words: Galaxy: disc – Galaxy: kinematics and dynamics – solar neighbourhood

1 INTRODUCTION

The orbital actions \((J_R, J_\phi = L_z, J_z)\) are a powerful tool for Galactic dynamics (Binney & Tremaine 2008, §3.5). They are excellent labels for stellar orbits and have an intuitive physical meaning. In axisymmetric gravitational potentials, actions are integrals of motion and are therefore ideal parameters for distribution functions that describe stellar components of the Galaxy, e.g. the disc (Binney & McMillan 2011; Sanders & Binney 2015) and the halo (Posti et al. 2015; Das & Binney 2016). Recently, several studies have made use of action-based dynamical modeling to learn more about the Milky Way’s gravitational potential (Bovy & Rix 2013; Pinfl et al. 2014; Trick et al. 2016) and chemo-orbital structure (Das et al. 2016; Sanders & Binney 2015; Bovy & Rix 2013). These studies modelled the Galaxy as axisymmetric and phase-mixed, i.e., stars are evenly distributed along orbits (in orbital angle space). But orbital actions are also powerful diagnostics of non-axisymmetric perturbations (Binney & Lacey 1988; Sellwood 2012; Fouvry & Pichon 2015; Monari et al. 2016, 2017a,b,c). Both long-lived and stochastic perturbations can lead to orbit diffusion that form distinct features in orbit space. In particular, ridges in \((L_z, J_R)\) space develop, seen both in numerical experiments (Sellwood 2012) and analytic (Fokker-Planck) models. Very locally, this manifests itself in streams and structure in \((U,V,W)\) velocity space. In particular, many of the moving groups observed in the \((U,V)\)-plane of the Solar neighbourhood (Dehnen 1998; Eggen 1996 and references therein)—among them the Hyades and the Hercules stream—are expected to have such a dynamic origin (e.g., Dehnen 2000; Famaey et al. 2005, 2007, 2008; see Section 3.2.1 for more details).

The second Gaia data release (DR2) on April 25, 2018 (Gaia Collaboration et al. 2018a) provided consistent high-precision measurements of positions, velocities, and stellar parameters for millions of stars, ushering in a new era in Galactic astronomy. Since Gaia DR2, several authors have been writing about the rich sub-structure that the Gaia data reveals. Arches and shells have been found in the disc’s velocity space (Gaia Collaboration et al. 2018b; Antoja et al. 2018), “snail shells” and ridges in space-velocity diagrams (Antoja et al. 2018; Kawata et al. 2018). While much sub-structure in the Galactic disc was indeed expected (cf. discussion in Bovy et al. 2009), observed in many previous observations.

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phase-mixed disc model. He also showed that Sirius and the Pleiades correspond to overdensities in action space.

This paper is organized as follows. In Section 2.1, we present the stellar sample that we are going to investigate. In Section 2.2, we give an introduction to actions and to action estimation—which the experienced reader is encouraged to skip—and mention the assumed gravitational potential model and estimation method employed in this work. To illustrate our naive expectations for the action distribution in a perfectly axisymmetric Milky Way, we generate and discuss mock data in Section 2.3. In Section 3.1, we present the distribution of Gaia DR2 stars in velocity and action space in different spatial bins. In Section 3.2, we have a closer look at the moving groups in the Solar neighbourhood. In Section 3.3, we will more closely investigate the new sub-structure that we found in action space. We discuss our results and conclude in Section 4.

2 DATA AND METHOD

The second data release of the Gaia satellite (Gaia Collaboration et al. 2018a) provides full 6D space coordinates for 7,224,631 stars: 2D positions (RA, Dec), parallaxes $\pi$, proper motions ($\mu_{\text{RA}}$, $\mu_{\text{Dec}}$) (Lindegren et al. 2018), and radial line-of-sight velocities $v_{\text{los}}$ (Katz et al. 2018) down to G=13 magnitude. The sample size is essentially set by the availability of radial velocity estimates. This data set is the by far largest, consistent sample to estimate precise orbits (i.e. orbital actions) for stars in an extended region around the Sun.

2.1 Sample Selection

2.1.1 Quality cuts

Meaningful action estimates require high-precision data, in particular good distance measurements (Coronado et al. 2018). We restrict our analysis therefore to the 3,738,840 stars that have relative parallax uncertainties $\delta \pi / \pi < 0.05$, which roughly translates into a relative distance error of 5%. This is precise enough for us to use $d = 1 / \pi$ as an acceptable distance estimate.

An additional quality cut is performed in the 3D space velocity with respect to the Sun,

$$
\frac{v_{\text{tot}}}{\text{km s}^{-1}} = \left \{ \left( \frac{v_{\text{los}}}{\text{km s}^{-1}} \right) ^2 + \left( \frac{2.43723 \text{mas yr}^{-1}}{\pi} \right) ^2 \times \left[ \left( \frac{\mu_{\text{RA}}}{\text{mas yr}^{-1}} \right) ^2 + \left( \frac{\mu_{\text{Dec}}}{\text{mas yr}^{-1}} \right) ^2 \right] ^{1/2} \right \} ^{1/2},
$$

with the factor 4.7623 accounting for the unit conversion. The measurement uncertainties in parallax, proper motion, and radial velocity are propagated and condensed to $v_{\text{tot}}$; we exclude all stars that have $\delta v_{\text{tot}} > 8 \text{ km s}^{-1}$. A third quality cut is performed in the astrometric excess noise, which is required to be smaller than 0.2 mas. This will exclude stars, e.g. binaries, for which the determination of parallax and proper motions might be prone to systematics (Lindegren et al. 2018).
and annuli in Solar distance using the coordinate transformations in Bovy (2015)’s velocities, centered at the position and velocity of the Sun, (We first convert the 6D coordinates from observables into 2.1.2 Coordinate conversion

3,564,940 stars. Further away from the Sun, the velocity distribution becomes rapidly washed-out, while consideration (see Section 2.3.2 for details). This figure illustrates the richness of sub-structure in Gaia DR2’s local Solar neighbourhood, both in velocity and the action plane. After these cuts we retain a high-quality sample of 3,564,940 stars.

2.1.2 Coordinate conversion

We first convert the 6D coordinates from observables into (X,Y,Z) positions and the corresponding (UHC, VHC, WHC) velocities, centered at the position and velocity of the Sun, using the coordinate transformations in Bovy (2015)’s galpy package. U moves towards the Galactic center, V is the velocity component in the direction of Galactic rotation, and W towards the Galactic North pole. For the Sun’s motion with respect to the Local Standard of Rest (LSR), we use (U⊙, V⊙, W⊙) = (11.1, 12.24, 7.25) km s⁻¹ (Schönrich et al. 2010), and convert the heliocentric (UHC, VHC) to (ULSR, VLSR). We assume (R⊙, φ⊙, Z⊙) = (8, 0, 0.025) kpc for the Sun’s position within the Galaxy (Jurić et al. 2008), and for the circular velocity of the Milky Way at the Solar radius \( v_{\text{circ}}(R_{\odot}) = 220 \text{ km s}^{-1} \). Using this, we can transform the \((X, Y, Z, U_{\text{LSR}}, V_{\text{LSR}}, W_{\text{LSR}})\) into Galactocentric \((R, \phi, z, v_R, v_T, v_z)\) coordinates.

2.1.3 Sub-samples in distance

We split the stars into three separate samples: The “local Solar neighborhood” with stars having distances \(1/\sigma < 200 \text{ pc}\), which corresponds to the spatial extent covered by the Hipparcos mission. The “extended Solar neighborhood”, which we define to be within 200 pc < \(1/\sigma < 600 \text{ pc}\). The “extended disc region”, which ranges from 600 pc < \(1/\sigma < 1.5 \text{ kpc}\) and captures regions in the thick disc and regions at radii quite different from the Solar circle. Outside of 1.5 kpc the data set becomes considerable incomplete due to the magnitude limit of Gaia’s Radial Velocity Spectrometer (RVS) (Cropper et al. 2018). The location and number density of these

Figure 2. The distributions of Gaia DR2 stars in the “local Solar neighborhood” (1/σ < 200 pc; left), in the “extended Solar neighborhood” (200 pc < 1/σ ≤ 600 pc; middle), and the “extended disc region” of Gaia DR2 (600 pc < 1/σ ≤ 1.5 kpc; right) in the following coordinates: Galactocentric meridional plane (top), radial and azimuthal velocities in the plane of the disc (middle), orbital actions in the Galactic plane, \((J_R, L_z)\) (bottom). In Panel 2(a) we use \(U\) and \(V\) with respect to the LSR as the radial and azimuthal velocities, and for the large spatial regions in Panels 2(b)-2(c) the equivalent Galactocentric velocities \(−v_R\) and \(v_T\) (as \(U\) and \(V\) have no physical relevance outside the Solar neighbourhood). The bin sizes in the 2D histograms are: 15 pc and 1 km s⁻¹ in position and velocity, \(0.065 \times [\text{pc km s}^{-1}]^{1/2}\) in \(\sqrt{R}\) and 0.0032 \(\times L_{z,0}\) in \(L_z\). In the upper panels, the location of the Sun is marked by an \(⊙\), the Galactic plane by a dashed line, and annuli in Solar distance \(1/\sigma\) in green. The small green dots in the lower panels at \(\sqrt{R} = 0\) reflect the radial range of the samples in consideration (see Section 2.3.2 for details). This figure illustrates the richness of sub-structure in Gaia DR2’s local Solar neighbourhood, both in velocity and the action plane.
three actions are usually defined to be \( J_R \), \( J_\phi \), and \( J_z \), commonly described by the star’s positions and velocities \((x(t), v(t))\), which exhibit a complex and rapid time evolution in the Galaxy’s gravitational potential: the orbit of the star. Action-angle space \((J_i(t), \theta_i(t))\) poses a useful alternative. This set of canonical conjugate coordinates has many convenient properties in axisymmetric galactic potentials. The three actions are usually defined to be

\[
\begin{align*}
J_R &= \frac{1}{2\pi} \int_{\text{orbit}} p_u \, du, \quad (2) \\
J_\phi &= \frac{1}{2\pi} \int_{\text{orbit}} p_T R \, d\phi = L_z, \quad (3) \\
J_z &= \frac{1}{2\pi} \int_{\text{orbit}} p_v \, dv, \quad (4)
\end{align*}
\]

where \((u, v)\) are prolate confocal coordinates in the meridional Galactocentric \((R, z)\) plane and \((p_u, p_v)\) the corresponding canonical momenta. \(\phi\) and \(p_T\) are the azimuth and the azimuthal velocity. The integration has formally to be done along the whole orbit. The orbit itself needs to be integrated in angle-space, the use of action-angle coordinates reduces the information content of the orbit effectively from six coordinates to the three actions only.

In a galaxy that exhibits non-axisymmetric structures like bars and spiral arms, the actions are not fully conserved anymore. \(L_z\), for example, will be subject to radial migration (Sellwood & Binney 2002). At a given point in time, the actions can, however, still be calculated.

For an in-depth introduction to action-angle coordinates we refer the reader to §3.5 in Binney & Tremaine (2008).

2.2.2 Action Estimation

The exact calculation of actions following Equations (2)-(4) is computationally expensive. However, in a special subset of galactic gravitational potentials, the Stäckel potentials, Equations (2)-(4) reduce to a single quadrature each, which can be fast and easily evaluated. There are algorithms that allow to estimate actions efficiently from a star’s observed Galactocentric cylindrical coordinates \((R, z, v_R, v_T, v_z)\) also in non-Stäckel potentials, often by making use of the properties of Stäckel potentials (Sanders & Binney 2016). One example is the Stäckel Fudge by Binney (2012). The closer a potential is to the Stäckel form, the more accurate the action estimation will be. Luckily, galaxy potentials like that of our Milky Way are—as long as we ignore the bar and spiral arms—quite close to a Stäckel potential (e.g., Batsleer & Dejonghe 1994; Famaey & Dejonghe 2003).

To estimate actions in the Milky Way, we make use of the galpy python package for Galactic Dynamics by Bovy (2015). galpy provides a simple-to-use axisymmetric gravitational potential model called MWPotential2014 with a power-law bulge, a Miyamoto-Nagai disc, and NFW
2.3 Axisymmetric mock data

We now illustrate what distribution we should expect in action space, \(n(L_z, J_R)\), and velocity space, \((U, V)\), in the Solar neighborhood for a perfectly axisymmetric Milky Way disc; this is shown in Figure 1, as a mock stellar distribution.

2.3.1 Generating mock data

The mock data are created via Monte Carlo sampling of a stellar distribution function (DF), following the procedure described in Trick et al. (2016), Appendix A. The Milky Way model consists of (a) the gravitational potential model that we used for the action estimation in this work, the \(MWPotential2014\) by Bovy (2015), (b) an axisymmetric action-based stellar disc DF, specifically the quasi-isothermal DF by Binney & McMillan (2011), and (c) a spherical selection function with sharp cut-off at \(d = 200\) pc around the Sun, as described and used in Trick et al. (2016, 2017). The scale parameters of the quasi-isothermal DF were chosen to be: disc scale length \(R^\text{disc}_0 = 2.5\) kpc, velocity dispersion \(\sigma^\text{disc}_R = 25\) km s\(^{-1}\), and exponential velocity scale length, \(h^\text{disc}_R = 7\) kpc (Bovy & Rix 2013). We drew \(\sim 310,000\) star particles from this DF. The Galactocentric radial and vertical velocity dispersions of all star particles in this mock data set are \(\sigma_R = 34\) km s\(^{-1}\) and \(\sigma_z = 22\) km s\(^{-1}\), and are therefore close to the velocity dispersion in our “local Solar neighbourhood” sample from Gaia DR2, \(\sigma_R = 37\) km s\(^{-1}\) \(\sigma_z = 20\) km s\(^{-1}\).

2.3.2 Signatures of the Survey Volume

The envelope of \(n(L_z, J_R)\) seen in Figure 1 simply reflects the spatial selection function of the sample. Stars with \(J_R \sim 0\) move on circular orbits; high-\(J_R\) stars have highly eccentric orbits. In the \(MWPotential2014\) the flat circular velocity curve has \(v_\text{circ}(R) \sim 220\) km s\(^{-1}\). Note that \(L_z = R \times T_R = R^\text{HC} \times v_\text{circ}(R)\) and \(R^\text{HC}\) is the guiding-center radius of the star’s orbit, basically the radius at which the star lives on average. At \(R = 8\) kpc, therefore \(L_z = 8\) kpc \(\times 220\) km s\(^{-1}\) \(\equiv L_{z,0}\). Only stars on circular orbits with \(L_z\) in the range

\[
\frac{L_z}{L_{z,0}} = \frac{R \pm \Delta R}{8\text{ kpc}} \times \frac{v_\text{circ}}{220\text{ km s}^{-1}}
\]

can reach into the survey volume of the sample. For the local sample, \(\Delta R = 0.2\) kpc and \(L_z(J_R = 0)/L_{z,0} \in [0.975, 1.025]\). For illustration these positions are marked by green dots in the lower panels of Figure 1 (and also in Figure 2). Stars with \(L_z\) outside of this range, i.e., stars that live on average in other regions of the galaxy, can only enter the survey volume, if...
they have higher $J_R$. The more a star’s $L_z$ differs from $L_{z,0}$, the more eccentric its orbit needs to be in order to be observable in the Solar neighborhood. This causes the triangular outer edge of the action distribution. Stars at $L_z/L_{z,0} < 1$ and located near the low-$J_R$ edge of the distribution are currently close to apo-center, stars at the $L_z/L_{z,0} > 1$, low-$J_R$ edge are close to peri-center.

Stars that live at large $R$ have large $L_z$ and vice versa. As many more stars exist in the inner Galaxy, we observe more stars with low $L_z$ and high $J_R$ in the local neighborhood, than stars with high $L_z$ and $J_R$. This causes $n(L_z, J_R)$ to be asymmetric with respect to the low-$L_z$ and high-$L_z$ edge of the distribution. The asymmetric distribution in the $V_{\text{LSR}}$ velocity in the upper panel of Figure 1 is related to this asymmetric drift.

3 RESULTS

We are now in a position to compare the actual distribution of $n(L_z, J_R)$ for this Gaia DR2 sub-sample to these simplistic expectations. We do this by both considering increasing volumes around the Sun, and by illustrating the mapping of substructure in $n(U, V)$ and those in $n(L_z, J_R)$. We will conclude with some investigations on the vertical action $J_z$ and the asymmetric distribution of radial velocities.

3.1 The 200 pc Solar neighborhood, and beyond

3.1.1 Structures in the Kinematic and Orbit Distribution

In Figure 2 we show in the upper panels the distribution of stars in the Galactocentric $(R, z)$ plane for the three distance annuli defined in Section 2.1.3. We also show the velocities describing the horizontal motions in the Galactic plane in the middle panel. For the sample $1/\sigma < 200$ pc we use the $(U_{\text{LSR}}, V_{\text{LSR}})$ velocities to describe radial and tangential motions. For the samples in the two larger volumes, we show the Galactocentric $(\sqrt{U^2 + V^2}, \sqrt{U^2 + V^2})$ velocities, which can be considered as the equivalent of $(U_{\text{LSR}}, V_{\text{LSR}})$ outside of the Solar neighborhood (apart from the different sign in the definition of $U_{\text{LSR}}$ and $V_{\text{LSR}}$, and a shift of 220 km s$^{-1}$ between $V_{\text{LSR}}$ and $V_T$). The lower panels in Figure 2 show a 2D histogram of the number of stars in action space, in particular in the actions that quantify the oscillations in the plane of the disc, $L_z$ and $J_R$.

The $(U_{\text{LSR}}, V_{\text{LSR}})$ plane of the local neighborhood (Figure 2(a), middle panel) reveals the well-known signatures of the moving groups in unprecedented detail and contrast, as has already been presented by Gaia Collaboration et al. (2018b). We note that this $(U, V)$ distribution is similarly skewed in $V$ direction due to the asymmetric drift as the axisymmetric mock data in Figure 1. In $U$, however, the mock data is perfectly symmetric, while the Gaia data shows not only much substructure, but also a correlation with stars having high $V$ also having higher $U$.

But the Gaia DR2 data now also reveal the rich substructure in the space of orbital actions, $n(L_z, J_R)$. Comparison to the axisymmetric mock data in Figure 1 shows a highly structured distribution. The high-density region at the low-$J_R$ edge of the distribution is divided into several seemingly discrete clumps; and there are several ridge-like overdensities in $n(L_z, J_R)$ extending towards high $J_R$ at almost constant $L_z$.

At distances beyond 200 pc, the velocity distribution becomes quite rapidly “blurry” and indistinct (Figure 2(b)-2(c), middle panels). In action space, however, there is still
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Figure 6. In-out asymmetry in the radial motions as a function of the actions \((L_z, J_R)\), illustrated through the fraction of stars that move radially inwards \((U_{\text{LSR}} > 0)\) in a Voronoi tessellation, each containing 100 stars. Blue means that more stars are moving in the direction of the Galactic center; red means that more stars are moving radially outwards toward the Galactic anti-center; white means that stars are symmetrically distributed in sign \((U_{\text{LSR}})\), as expected from an axisymmetric Galaxy model. The left and right panel are identical, except that we have overplotted the ellipses from Figure 5 on the right panel to demonstrate that many, but not all, regions of high density identified by eye also correspond to regions of highly asymmetric distributions in \(U_{\text{LSR}}\).

3.1.2 The influence of measurement uncertainties

It is necessary to explore to which extent the measurements in the observables \((\mu, \mu_\text{par}, v_{\text{los}})\) propagate into the space of \((L_z, J_R)\). In Fig. 3 we illustrate the extent of the morphology in \(n(L_z, J_R)\) that could be affected by measurement uncertainties. For 100 random stars, we converted 100 Monte Carlo samples each drawn from the Gaia uncertainties into action space. The majority of stars at close distances \((1/\sigma < 200 \text{ pc})\) have small error in parallax. We also note that the uncertainty distributions are much narrower with respect to stars at larger distances where the uncertainties tend to spread more in action space. This is expected to cause some bluriness in action space that could hide possible structures. Also, we observe that the stars that populate the larger distance regime at 600 pc \(< 1/\sigma < 1.5 \text{ kpc}\) tend to have larger fractional errors in parallax.

Overall, the uncertainties are much smaller than the observed sub-structures, especially in the regime \(1/\sigma < 200 \text{ pc}\). So we expect that these action features indeed exist in the Milky Way and are not just observational relics.

3.2 Mapping moving groups into action space

3.2.1 Reviewing Moving groups

The \((U, V)\) plane of the Solar neighbourhood reveals overdensities of stars that appear to move on common trajectories (Dehnen 1998). Among them are the Sirius, Coma Berenices, the Hyades and Pleiades, and the Hercules stream (see Figure 4, left panel). Notwithstanding the star clusters of the same name, these groups do not correspond to overdensities in space.

Several origins have been proposed for these moving groups. (a) They could be open clusters, born together, but no longer gravitationally bound, and now dispersing (see series of papers by Eggen, starting with Eggen (1958), and also references therein). (b) They could be accreted and disrupted sub-halos, as predicted by hierarchical galaxy formation theory (Helmi et al. 1999). The Arcturus stream at \(V \sim -100 \text{ km s}^{-1}\) and spreading a wide range in \(U\) (Williams et al. 2009), for example, appears to have an extragalactic origin (Navarro et al. 2004; Zhao et al. 2014). (c) They could be the local manifestation of dynamic resonance effects caused by non-axisymmetric perturbations in the Galactic disc, like the bar (Dehnen 2000; Minchev et al. 2010), or spiral waves (De Simone et al. 2004; Quillen & Minchev 2005; Monari et al. 2018). (d) Another dynamical origin could be perturbations of the disc due to sub-halo mergers (Minchev et al. 2009; Monari et al. 2018).

The moving groups appear to have a wide range of stellar ages (Famaey et al. 2005; Antoja et al. 2008) and average metallicities that stand out from the stellar background distribution (Bensby et al. 2007, 2014; Bovy & Hogg 2010; Pompéia et al. 2011) — both consistent with a dynamic rather than a common birth origin. In particular, the Hyades group might be caused by an inner Lindblad resonance of spiral arms (Quillen & Minchev 2005; Sellwood 2010; McMillan 2011, 2013) and the Hercules stream could be due to the
Figure 7. Overdensities in $n(L_z, J_R)$ and in-out asymmetry of the radial motion for regions outside beyond $1/\omega = 200$ kpc around the Sun. The two left (identical) columns and the right column show in grey scale the logarithmic number density of stars in action and velocity space, respectively, analogous to Figure 5. Overdensities in $n(L_z, J_R)$ have been identified and marked by ellipses in the second column. Stars, that fell into these ellipses, were located in Galactocentric velocity space ($-v_R, v_T$) and contours of 10 and 90 stars per $(1 \text{ km s}^{-1})^2$ velocity bin were overplotted in the same color. The third and fourth column show the (identical) Voronoi tessellation for the fraction of stars that move radially inwards toward the Galactic center ($v_R < 0$), analogous to Figure 6. In the fourth column we simply overplot the ellipses marking the overdensities for comparison. We find, that—except of some blurriness due to measurement uncertainties (see Figure 3)—the overall morphology in terms of the location of overdensities and of asymmetric radial motions in action space remains qualitatively the same at any distance.

outer Lindblad resonance of the bar (Dehnen 2000; Monari et al. 2017b; Hunt & Bovy 2018; Hattori et al. 2018).

In addition to the $(U, V)$ plane, the moving groups could also be identified as overdensities in orbital quantities, like energy, angular momentum, eccentricity etc. (e.g., Arifyanto & Fuchs 2006; Klement et al. 2008).

Before Gaia DR2, quantification of the extent of moving groups in the $(U, V)$ plane was more difficult, due to the lesser quality and quantity of existing data sets (e.g. Bovy et al. 2009). Katz et al. (2018) have just recently identified arches with nearly constant $V$ and spanning a wide range of $U$ in Gaia DR2 data within $d = 200$ pc, that coincide with known moving groups.

3.2.2 The moving groups in action space

In Figure 4, we have used the peak $(U, V)$ positions recorded by Katz et al. (2018) for the moving groups Sirius, the Hyades and Pleiades, and the two Hercules sub-streams, and drawn ellipses by eye around them to encompass the most prominent regions of the overdensities. The stars within these ellipses were then mapped into action space. Contours encompassing 95% of the stars of each group are shown in the same colors in the right panel of Figure 4 in the $(L_z, J_R)$ plane. It becomes immediately obvious that the highest density peaks in action space correspond to the moving groups. This is not surprising, as stars in the local Solar neighbourhood share almost the same $(R, \phi, z)$ position. If they also have similar $(U, V)$ velocities in the disc plane, it is very likely that they are overall on very similar orbits and therefore also have similar actions describing the horizontal motions, i.e. $(L_z, J_R)$.

The groups are confined to well-defined regions in action space, albeit slightly more spread out than in velocity space. There appears to be a slight tendency of the groups at low $J_R$ to extend into some of the observed high-$J_R$ ridges at almost constant $L_z$. We will look at this further in the next section.

Our Figure 4 should be compared to Figure 10 in Sellwood (2010), who did the same exercise of mapping moving groups to action space with Hipparcos/GCS data. The most prominent feature in his study was the Hyades stream; other structures were barely visible. This illustrates once more how data from Gaia DR2 can and will revolutionize our knowledge about the Galaxy.

3.3 The rich sub-structure in action space

3.3.1 Mapping features in $n(L_z, J_R)$ to $(U, V)$

In the previous section we have mapped known and named overdensities in $n(U, V)$ into action space. As we saw in Figure 2, with Gaia DR2 data we will soon be able to identify...
they move from the outer Galaxy towards the inner Galaxy and large (Figure 5). The two contours were drawn at 5 and 20 stars per moving groups and extending towards high-\( \ln \) in each feature.

Stars at \( L_z \) of course been noted before by several authors (see, e.g., An-\( \nu \) toja et al. 2015 and references therein). Stars at \( L_z > 0 \) and \( R < 200 \) pc away from the disc plane have in general much higher \( J_z \). Bins have widths 0.13[kpc km s\(^{-1}\)]\(^{1/2} \) in \( \sqrt{J_R} \) and 0.0067[\( L_z \)] in \( L_z \) and are only plotted if they contain more than 10 stars. This figure illustrates that the sub-structures in \( n(L_z, J_R) \), investigated in the previous figures, are not just stellar overdensities, but also have lower vertical actions; this may be expected if the features in \( n(L_z, J_R) \) are responses to resonances in the disc.

many more structures both in velocity as well as in action space.

Here, we proceed now in the opposite direction as in Section 3.2, pick out sub-structure in \( n(L_z, J_R) \), mark them with colorful ellipses (left panels in Figure 5), and map the corresponding stars into the \((U, V)\) plane (right panel in Figure 5). The two contours were drawn at 5 and 20 stars per \( (1 \text{ km s}^{-1})^2 \) bin and illustrate the different number densities in each feature.

The ridges in \( n(L_z, J_R) \), starting at the location of known moving groups and extending towards high-\( J_R \), turn out to map to the arch-like extensions at high |\( U \)| that were observed by Katz et al. (2018). Both stars moving towards the Galactic center \((U \gg 0)\), as well as away from the Galactic center \((U \ll 0)\), contribute to these vertical features—albeit with different number of stars. We will look into this in more detail in Section 3.3.2.

### 3.3.2 Asymmetric population of stars along the orbits

In a completely phase-mixed, axisymmetric galaxy, one would expect that the stars along non-resonant orbits are evenly distributed in the orbital phases (i.e., the angles \( \theta_i \)). An eccentric orbit crossing the Solar neighbourhood should then have the same number of stars moving outward and inward. This need not hold true if the orbital angles are not uniform, or if it is a resonant orbit.

In Figure 5 we found that the number density of stars on similar orbits are asymmetrically distributed in \( U \). This has of course been noted before by several authors (see, e.g., An-\( \nu \) toja et al. 2015 and references therein). Stars at \( L_z/L_z,0 > 1 \) and large \( J_R \) are more likely to have positive \( U \) velocities, i.e., they move from the outer Galaxy towards the inner Galaxy (i.e. the Sirius stream and its extensions in yellow). Vice versa, stars at \( L_z/L_z,0 < 1 \), in particular the Hyades (pink) and Hercules streams with its extensions (green/blue), live on average in the inner Galaxy and are currently more likely to move outwards.

To illustrate this further, we have in Figure 6 color-coded a Voronoi tessellation of action space with each 100 stars per bin by the fraction of stars moving towards the Galactic center. It appears that stripes of predominant outward and inward movements alternate with each other when going from small to large \( L_z \). Overplotting the ellipses from Figure 5 marking overdensities in \( n(L_z, J_R) \), we see that many, but not all, density features correspond to regions of high asymmetric motions. Coma Berenices (red) and the Pleiades (purple) for example appear to be quite phase-mixed.

### 3.3.3 Action sub-structure beyond the Solar neighborhood

We saw in Figure 2 that in the stellar samples outside of the Solar neighborhood, \( 1/|\sigma| > 200 \) pc, action space still exhibits some sub-structure. We proceed analogously to Figure 5 in Section 3.3.1, and select overdensities in \( n(L_z, J_R) \) in the samples at large distances, as shown in the left two columns of Figure 7. Even though the sub-structure seems to blur out (due to measurement uncertainties as illustrated in Figure 3), we find that several of the overdensities are located at similar positions in \( (L_z, J_R) \) as in the local sample \( 1/\sigma < 200 \) pc: The feature(s) at high \( J_R \) related to the Hercules stream (green/blue), the Sirius stream (yellow), the Hyades (dark pink), and the small features above the Hyades stream (light pink and light purple) appear in all three spatial samples.

\[ \text{Figure 8. The mean vertical action} J_z \text{ of stars falling into the same bin in } (L_z, J_R) \text{ space, for the "local" (left) and "extended" (middle) Solar neighborhood, and the "extended disc region" (right). Note that the range of the colorbars is different, as stars more than } \sim 200 \text{pc away from the disc plane have in general much higher } J_z. \text{ Bins have widths } 0.13\text{[kpc km s}^{-1}\text{]}^{1/2} \text{in } \sqrt{J_R} \text{ and } 0.0067\text{[}L_z\text{]} \text{in } L_z \text{ and are only plotted if they contain more than 10 stars. This figure illustrates that the sub-structures in } n(L_z, J_R) \text{, investigated in the previous figures, are not just stellar overdensities, but also have lower vertical actions; this may be expected if the features in } n(L_z, J_R) \text{ are responses to resonances in the disc.} \]
Secondly, we illustrate the asymmetry in radial motions \( v_R \) for the \( 1/\sigma > 200 \) pc samples in a Voronoi diagram in the third and fourth column of Figure 7. The color-coding is analogous to Figure 6, with red for predominant outward motions, and blue for inward motions. The asymmetry pattern remains qualitatively the same for all three volumes that we consider.

Thirdly, we map the overdensity ellipses from action space to the \((-v_R, v_T)\) velocity plane, analogous to the mapping to \((U, V)\) for local stars. This is shown in the right column of Figure 7. Even though similar trends as in Figure 5 (right panel) can be seen, the different sub-structures are strongly overlapping in the velocity plane the further away from the Sun we go. This illustrates that action space outside of the Solar neighborhood might be better for investigating orbit structure than velocity space (see also McMillan 2013).

3.3.4 Features in \( n(L_z, J_R) \) and their vertical action

So far, we have restricted our investigations of sub-structure in action space on the actions that govern the motion in the plane of the disc, \( L_z \) (circular motion) and \( J_R \) (radial motion). In the epicyclic approximation—which is in general valid for most orbits in the thin disc—the radial and vertical motions are decoupled from each other, and structure in the plane of the disc does not necessarily translate into structure in the vertical direction. Radial migration, for example, is expected to change \( L_z \) (Sellwood & Binney 2002) and \( J_R \), but conserve the vertical action \( J_z \) on average (Solway et al. 2012; Vera-Ciro & D’Onghia 2016).

To investigate sub-structure in vertical orbit space, we calculate for each bin in the \((L_z, J_R)\) plane \((\Delta\sqrt{J_R} = 0.13 [\text{kpc} \, \text{km} \, \text{s}^{-1}]^{1/2}, \text{and} \Delta L_z = 0.0067 [L_z]_0)\) the mean vertical action \( \langle J_z \rangle \) and show the result in Figure 8. In all three spatial bins, we see again the same sub-structure as in Figures 2, 5, and 7. But this time not in stellar number density, but in the value of the mean vertical action.

This shows that \( n(L_z, J_R) \) overdensities have lower average vertical actions, which has two implications. First, it appears that the sub-structure in \( (L_z, J_R) \) is indeed physical and not due to, e.g., measurement uncertainties. Measurement uncertainties could explain stars at large \( J_R \), but not why the same stars should have at the same time small \( J_z \) (see Figure 1 in Coronado et al. 2018). Second, the sub-structure seems to be most prominent in the in-plane orbits.

4 DISCUSSION AND CONCLUSION

4.1 Summary

In this work we have shown that there is a great deal of substructure in the orbit-space distribution of Galactic disc stars within \( \sim 1.5 \) kpc. This has been possible for the first time thanks to Gaia DR2’s high-precision measurements of millions of stellar positions and velocities. The distribution of orbital actions \( n(J_R, L_z) \) exhibit a wealth of clumps and ridges. At low radial action \( J_R \) these map to the known UVW moving groups in the Solar neighbourhood. But there are also ridge-like features pointing towards high \( J_R \) at similar \( L_z \), which are not compact UVW clumps in the Solar neighbourhood. We can have confident that these \( n(J_R, L_z) \) features are physical as (i) the typical measurement uncertainties are smaller for this sample than the size of the observed structures; (ii) these overdensities in \( n(J_R, L_z) \) have low mean \( J_z \), stay very close to the disk; (iii) many correspond to regions of highly asymmetric radial motion (in-out imbalance); and (iv) we have observed the same features in all distance regimes out to \( 1/\sigma = 1.5 \) kpc. These features appear to reflect the large-scale orbital sub-structure of the Galactic disc, which appears to be intricate throughout the observed volume.

We now re-summarize some of the empirical findings, along with a cautious and preliminary interpretation.

4.2 Orbit structure beyond the Solar neighborhood

Figures 2 and 7 have illustrated that beyond the Solar neighborhood (100-200 pc) velocity space is less suitable to reveal orbit sub-structure as compared to action space, for plausible reasons: disc orbits allow three coordinates to describe the position on (or the phase of) an orbit (e.g., the angles) and three conjugate momenta to label the orbit (e.g., the actions). In the Solar neighbourhood, all stars have basically the same position \( \mathbf{x} \), so the conjugate momenta, the velocities \( \mathbf{v} \), are good proxies for orbit labels. In large spatial regions, velocities at widely different positions cannot be compared to each other in a meaningful way. There are different approaches to circumvent this. (i) The velocity distributions are independently investigated and modeled in different, small spatial bins (see, e.g., Antoja et al. 2012; Bovy 2010; McMillan 2013; Gaia Collaboration et al. 2018b). (ii) Resorting to action-angle space, where orbital phases and labels can be globally investigated and modeled (see, e.g., Sellwood 2010; McMillan 2011). But ultimately, it appears that an orbit description, e.g. through actions and angles, is the more sensible approach beyond the small volumes that Hipparcos data had dictated.

4.3 Asymmetric radial motions

In Section 3.3.2 we showed the dramatic asymmetries in stellar number counts in \( U_{LSR} \) or \( v_R \), as a function of \((J_R, L_z)\). We refer the reader to the illuminating Figure 7 in McMillan (2011), which shows the relation between the orbital phase angles \( (\theta_R, \theta_\phi) \) and the \((U_{LSR}, V_{LSR}) \) velocities. A population phase-mixed in the radial phases \( \theta_R \) should therefore have a symmetric distribution in \( U_{LSR} \). Especially the distribution of azimuthal phase \( \theta_\phi \) is, however,—as McMillan (2011) shows—strongly affected by selection effects. This radial motion imbalance therefore implies that many orbits in the Galactic disc (7-9 kpc) are either not phase-mixed along the orbit, or on resonant orbits.

We found that density peaks of the moving groups in the local neighbourhood (in particular Sirius and Hercules) correspond to overdensities aligned with the low \( J_R \) edge of the \( 1/\sigma < 200 \) pc action distribution (Figure 4). No such alignment with the edges are seen for the action substructure in the \( 1/\sigma > 200 \) pc samples (Figure 7, left). Figures 6 and 7, which investigate the asymmetry in radial motions, all show the same stripe-pattern, irrespective of the selection-function-induced edge of the distribution. We deduce that the moving groups in \((U, V)\) are indeed just the
local, selection-effect-affected manifestations of some global orbital action-angle structure.

The next step in the study of orbit sub-structure in Gaia DR2 would be to explicitly calculate and investigate the angles, following Sellwood (2010) and McMillan (2011). In any case, knowing and correcting for the survey selection function will be crucial when interpreting velocity, action, and/or angle distributions.

4.4 The nature of the action sub-structure

We have been able to show that the clumps are related to the known moving groups, and the ridges to the newly discovered arches in velocity space (Gaia Collaboration et al. 2018b). This leaves us to explain the “nature” of the various clumps and ridges that we observed in action space. Gaia Collaboration et al. (2018b) noted that similar arch-like structures were found to be caused by resonances of the bar in simulations by Dehnen (2000) and Fux (2001). In the action/angle-based perturbation studies by Monari et al. (2017a,c) the bar caused an arch-like shearing in velocity space.

Studies that investigated the effect of resonances in action space (Sellwood 2010, 2012; McMillan 2011; Fouvry et al. 2015a,b), found that resonances cause narrow ridges at approximately constant $L_z$ in action space. Using various approximations of the Fokker-Planck equation, Fouvry et al. (2015a,b) demonstrated that these ridges coincide with directions of rapid orbit diffusion (for tightly wound spirals). Stars located at the $L_z$ corresponding to the radius of the resonance and which had originally low-eccentricity orbits, move on orbits that become progressively more eccentric (i.e., larger $J_R$) due to the resonance, causing the steep ridges in $n(L_z, J_R)$. The exact direction of the ridge depends on the underlying resonance (e.g. ILR, OLR or co-rotation Fouvry & Pichon 2015), but the behaviour is quite complex. The strength of the ridge depends (i) on the strength of the diffusion coefficient, which in turn depends on the position in orbit space, and (ii) on the velocity dispersion of the underlying tracers, with kinematically cold populations in the Galactic disc being affected the most. This could be an explanation why we see the action substructure most prominently at low $J_z$, i.e., in the in-plane orbits (see Section 3.3.4).

4.5 Caveats

One caveat when investigating actions is the uncertainty in our knowledge about the overall shape of the Milky Way’s gravitational potential. Also, while in an axisymmetric potential the actions are well-defined and integrals of motions, the Galaxy is clearly not axisymmetric. Any action calculation per se will therefore only be an action estimation. We emphasize that we have treated the actions in this work simply as an informative coordinate system to label the orbits that the stars currently are on, under the assumption of an axisymmetric gravitational potential model for the Milky Way (MWPotential2014 by Bovy 2015).

Secular evolution and orbital diffusion might need to be evoked in the future to explain the observed orbital structure. Here, we only investigated the status quo using actions to characterize orbits.

In the long-term, we expect that Gaia data will also help to improve measurements of the Galaxy’s gravitational potential, allowing more accurate action estimation (e.g., Trick et al. 2016; Watkins et al. 2018).

The exact location of the features in action space depends, among others, on the choice of the Solar motion with respect to the Local Standard of Rest. In this work we use $(U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25)$ km s$^{-1}$ by Schönrich et al. (2010). We have also performed the tests in this work using the measurement by Tian et al. (2015), $(U_\odot, V_\odot, W_\odot) = (9.58, 10.52, 7.01)$ km s$^{-1}$, from LAMOST data. The action features shift up to $\Delta L_z/L_z,0 = 0.02$ along the lower $J_R$ edge of the distribution. Qualitatively the shape of the structures does not change, however.

4.6 Concluding remarks

It is clear that the rich structure in action space contains a wealth of information about non-axisymmetric perturbations and resonances in the Galactic disc. The fact that Fig. 2 suggests four to eight separate ridges at different orientations in the $(L_z, J_R)$ plane suggests that more than one (resonance) mechanism might be at work. As Sellwood (2010) and McMillan (2011) noted, action space alone will, however, not be sufficient to determine which kinds of resonances are at work. The modeling of this substructure is therefore highly complex and beyond the scope of this paper.

In the past, action estimations have largely been dominated by measurement uncertainties (Coronado et al. 2018) and substructure in action space was forgiving when using axisymmetric models to describe the Galaxy (Trick et al. 2017). Gaia DR2 might finally mark the beginning of an era where the limitations of our models to capture the complexity of the data will be the limitations to our knowledge about the Milky Way.

ACKNOWLEDGEMENTS

The authors thank Paul McMillan, Simon White, and David Hogg for helpful comments on early versions of some figures in this work. J.C. acknowledges support from the SFB 881 program (A3) and the International Max Planck Research School for Astronomy and Cosmic Physics at Heidelberg University (IMPRS-HD). H.W.R. received support from the European Research Council under the European Union’s Seventh Framework Programme (FP 7 ERC Grant Agreement n. [321035].

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