Footprints of the Sagittarius dwarf galaxy in the Gaia data set

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ABSTRACT

We analyse an N-body simulation of the interaction of a Sagittarius-like dSph (Sgr) with the Milky Way (MW), looking for signatures which may be attributed to the orbital history of Sgr in the stellar-phase space volume around the Sun in light of the recent Gaia DR2 discoveries. In this simulation, Sgr excites coupled oscillations in the vertical and radial directions, a bar and bisymmetric spiral which quickly winds up over the last Gyr of its evolution. The repeated impacts of Sgr with the MW are qualitatively, and to a large degree quantitatively able to reproduce many of the recently uncovered features in the 6D Gaia samples presented in Katz et al. and Antoja et al. We find that the complex pattern in the velocity field is well described by a model with tightly wound tidally excited spirals from Sgr’s impacts. This is the first N-body model able to explain so many of the features in the data on different scales in a consistent fashion. The failures of the models, such as the excess amplitudes of the signal compared to the data, call for the need of more detailed modeling through adapted numerical methods tailored to the Milky Way (using test particle and full N-body simulations) and its interaction with its principal perturber in the last Gyr. These should help us gain insight into the excitation of spiral arms, the bar and the mass-loss history of the Sgr dwarf. The successes presented here suggest that this goal is within reach.

Key words:
Galaxy: structure - Galaxy: kinematics and dynamics - Galaxy: evolution - Galaxy: formation - Galaxy: disc - Galaxy: halo

1 INTRODUCTION

Gaia’s second data release has brilliantly revealed the richness of substructure in our Galactic disk in unprecedented and unforeseen ways.1 These should be loosely understood as integrals since the Milky Way is non-axisymmetric and most likely a non-integrable system, however together with actions these quantities can be used as coordinates to understand the MW to a zeroth degree.

However other out-of-equilibrium features might be excited through external agents as well, such as mergers, which produce ringing in the $U - V$ plane. These arching features become clearly visible in the space of integrals $E - L_z$. The existence of substructure in the form of moving groups of stars around the Sun was first pointed out many decades ago and interpreted as a signature of disrupted clusters (Eggen 1969). Analysis of the Hipparcos data (Dehnen 1998) offered additional insight that such groups could be excited by asymmetries in the disc, such as the bar or spiral arms (Dehnen 2000). The existence of substructure in the form of moving groups of stars around the Sun was first pointed out many decades ago and interpreted as a signature of disrupted clusters (Eggen 1969). Analysis of the Hipparcos data (Dehnen 1998) offered additional insight that such groups could be excited by asymmetries in the disc, such as the bar or spiral arms (Dehnen 2000).

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measurements of asymmetries in the $U-V$ plane as a function of height, such as for the Coma Berenices seen in GALAH (Quillen et al. 2018) and in RAVE (Monari et al. 2018) have also indicated another hint for a merger origin of this moving group. The Sagittarius dwarf spheroidal [Ibata et al. 1994], has long been suggested to be a potential perturber to the Milky Way Galactic disc [Ibata & Razoumov 1998; Dehnen 1998; Bailin 2004]. Indeed using test particle simulations Quillen et al. (2009) showed that a Sgr-like satellite could induce perturbations to a disc in the form of a warp, spiral structure as well as streams in the UV plane. However, only recently has it been possible to assess the impacts of Sagittarius on the Galactic disc with high-resolution live N-body simulations [Purcell et al. 2011; Gomez et al. 2012b; 2013; Laporte et al. 2018a,b]. These are necessary in order to study the excitation of vertical density waves which are known to be sustained by self-gravitating discs [Hunter & Toomre 1969] (1998), an aspect which cannot be captured by simple phase-mixing models of tracers subject to impulsive perturbations.

Direct first evidence of ringing in the Milky Way using the Schuster et al. [2006] and SEGUE F/G dwarf stellar sample was measured by Gomez et al. (2012b) who attributed the signal to a passage with the Sgr dSph. Coincidentally, signatures of vertical oscillations in the disc became apparent as local asymmetries in velocity distributions seen in spectroscopic surveys [Widrow et al. 2012; Williams et al. 2013; Carlin et al. 2013] and large scale arc-like features above and below the disk plane in the outer disc [Newberg et al. 2002; Crane et al. 2003; Grillmair 2006; Martin et al. 2014; Sharma et al. 2010].

Since then, Antoja et al. (2018) used the Gaia second data release to uncover a series of substructures in and around the solar neighbourhood, confirming unambiguously that the galaxy is out-of-equilibrium and in a middle of a phase-mixing process. The source for the perturbation has been suggested to be related to Sgr but other degeneracies remain (e.g. spiral arms, bar). However, the authors used a toy model from Minchev et al. (2009) to estimate the time of impact/disturbance in the solar neighbourhood. Although this toy-model only considers phase-mixing for a set of tracers in a given potential (i.e. neglecting self-gravity), interestingly they find values which are consistent with the timescales for Sgr’s last pericentric passage (Laporte et al. 2018b).

In this paper we explore whether any of the various features in the recently reported substructures in velocity space of Gaia DR2 [Antoja et al. 2018] can be attributed as clear signals to Sgr’s orbital history. We do so, using simulations from the suite of numerical N-body experiments in [Laporte et al. 2018b]. These simulations follow the orbit of Sgr like galaxies around a Milky Way-like host from the first pericentric passage to the present-day. These were the first sets of numerical experiments to successfully reproduce the excitation of the Monoceros Ring and various associated substructures (e.g. ACS) while producing vertical fluctuations in the solar neighbourhood in good agreement with the constraints set by [Widrow et al. 2012] (see section 2.2 for more details).

This paper is organised as follow. In section 1 we describe the simulations used here. In section 2 we present maps of velocity in regions around the Sun which we compare to the recent results of Katz et al. (2018) and what these may reflect in the Galaxy. In section 3, we compare models to the recent results of Antoja et al. (2018), Monari et al. (2018), Quillen et al. (2018) on substructure in the solar neighbourhood. In particular, we look for signs of substructure and phase-mixing which can be related to the Sgr dwarf spheroidal. We discuss various qualitative successes of our models and highlight areas where these will need to be refined in the coming years.

2 PRIOR WORK

2.1 Numerical methods

The simulations used in this paper are taken from Laporte et al. (2018b). These were a series of numerical live N-body experiments of the interaction Sgr with the Galactic disc as well as a series combined with the effect of the LMC on a first infall orbit Besla et al. (2007) for which separate N-simulations were also presented in Laporte et al. (2018a). We note that these experiments significantly improved on earlier works on the impact of Sgr on the disc [Purcell et al. 2011] (e.g.). Indeed, all prior works used initial conditions which were too simplistic ignoring the effect of earlier passages of Sgr in exciting vertical perturbations to the disc through the dark matter halo wake [Weinberg 1989; 1998] and thus were unable to reproduce outer disc structures similar to the Monoceros Ring. One exception to this, is the live N-body simulations of Dierickx & Loeb (2017) which also considered the full orbit of the Sgr progenitor from the virial radius to its present-day location, but these authors focused solely on the properties of the remnant stream, not the reaction of the disc.

Here we give a brief description of our simulations suite, but the interested reader is referred to relevant contributions for more details. In these simulations, the host MW had the following properties: a dark halo of $M_h = 10^{12} M_{\odot}$, an exponential disc of $M_{\text{disc}} = 6 \times 10^{10} M_{\odot}$, with a scale radius of $R_d = 5.3$ kpc and scale height of $h_d = 0.35$ kpc and a central bulge with a mass of $M_{\text{bulge}} = 10^{10} M_{\odot}$. The mass model adiabatically contracted following Blumenthal et al. (1980), steepening the dark matter profile to lead to a final mass model with a circular velocity of $V_{\text{circ}} = 239$ km s$^{-1}$ at $R_0 = 8$ kpc. Four different models for Sgr are considered with varying masses ($M_{\odot} \sim 6 \times 10^{10} - 10^{11} M_{\odot}$) and concentrations within the scatter of the mass-concentration relations [Gao et al. 2008; Ludlow et al. 2014]. The simulations end with a final remnants masses in agreement with current estimates [Frinchaboy et al. 2012] producing streams in agreement with the M-giants from Majewski et al. (2003) and orbital timescales for the Sgr dwarf varying between $t_{\text{orb}} \sim 0.4$ Gyr and $t_{\text{orb}} \sim 1.0$ Gyr in the last stages.

2.2 Comparison of simulations and prior observations

Some of the various quantitative and qualitative successes of these runs with observations prior to the Gaia revolution are listed below:

- Vertical density and velocity perturbations [Gomez et al. 2013] in the solar neighbourhood in agreement with
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2.3 Analysis of the simulations: L2 model

Given that the simulations were not initially aimed at reproducing the exact properties of the Galactic disc and Sagittarius’ orbit simultaneously, we allow ourselves to analyse the Galaxy in a more general fashion in the spirit of Laporte et al. (2018c), as it is not clear whether it could reproduce any of the features seen in the Gaia volume. However, if a qualitative match is found, it may still prove interesting to study what this could possibly tell us about the Galaxy in relation to its interaction with Sgr. In this contribution, we focus on the L2 model which was presented in Laporte et al. (2018c).

Figure 1 shows a series of surface density maps of the MW analogue subject to impacts with Sgr during the last two pericentric passages. These correspond to times \( t \approx -0.5, 0.0 \) Gyr respectively. We note that in previous passages, the Sgr has excited spiral structure which gradually winds up. In the very last passage at \( t \approx 0.0 \) Gyr, a strong bi-symmetric spiral is excited which quickly winds up and the disc goes bar unstable. In the L2 model, Sgr reaches its present-day position by \( t \approx 0.4 \) Gyr. At this point, Sgr with \( M \approx 10^9 \) \( M_\odot \) bound mass, is on its course to full disruption and its subsequent evolution does not affect the disc in any visible fashion.

In addition, we note that for our suite of models which varied masses and orbits for Sgr, the last pericentric passage of Sgr was found to be anywhere between 0.4 – 1 Gyr in the past. Given this uncertainty window, we allow ourselves to search for a snapshot where the disc qualitatively matches the Gaia field with the additional constraint of having the bar facing at 30-40 degrees (Dremlle 2000). For the L2 model, this allows us to consider the state of the Galaxy within \( \Delta t \approx 500 \) Myr past the “present-day” snapshot \( t \approx 0.4 \) Gyr.

3 RESPONSE OF THE DISC IN THE GAIA VOLUME

As part of the official DR2 release papers, Katz et al. (2018) presented a preliminary analysis of the kinematics of the disc as revealed by the 6-D Gaia solution in roughly a box bound by \(-4 < Y/\text{kpc} < 4 \) and \(-5 < X/\text{kpc} < 12 \). They noted a series of interesting features and in the median \( V_R(x,y), V_Z(x,y) \) and \( V_y(x,y) \) planes (see their Fig. 10):

- Median radial velocity variations of \(-10 < V_R/\text{km}\text{s}^{-1} < 10 \) interpreted as the existence of successive intertwined spiral arms (Reid et al. 2014) or the 2-spiral arm model from Drimmel (2000)
- A warp revealed by the median vertical kinematical component of the disc. Increasing from \( V_Z \approx 0 \) km s\(^{-1}\) to \( \sim 4 \) km s\(^{-1}\) in the range \( 6 < R/\text{kpc} < 12 \) along the \( 0^\circ \) line in azimuth connecting the Sun to the Galactic Center. This warp was further put into evidence using both old and young stellar tracers (Poggio et al. 2018).
- Median azimuthal velocity variations in the midplane between \( \sim 220 \) km s\(^{-1}\) and \( \sim 235 \) km s\(^{-1}\)

In this section, we compare the spiral arm patterns seen in the Gaia DR2 data (Katz et al. 2018) to the outcome of the Galactic disc being perturbed by the Sgr, to see if any reasonable match can be found in amplitude, scale and/or orientation. Indeed we noticed in the earlier section that after last pericentric passage, Sgr induces a strong spiral structure which quickly winds up over a period of \( \sim 700 \) Myr.

Using our L2 model, we looked for snapshots where a qualitative match is visible in 2D maps of \( V_R, V_Z, V_y \) and \( V_x \), with the added requirement that the MW bar should be oriented at a thirty degree angle with respect to the observer. We found such a match at \( t \approx 0.8 \) Gyr (i.e. after \( \Delta t \approx 400 \) Myr), or the equivalent of two rotations of the Sun past \( t \approx 0.4 \) Gyr which also happens to put the bar at \( \sim 30 - 40^\circ \) orientation.

In top panels of Figure 2, we present our simulated 2D maps of median \( V_R, V_Z, V_y \) which closely reproduce the features in Katz et al. (2018) - see their Figure 10. We also complement these maps with 2D projections of the surface density contours overlaid on them. In the bottom panels of Figure 2, we show maps of the density contours, median height \( < Z > \) and standard deviation in height \( \sigma Z \) as a proxy for the flaring of the disc.

We see that our median radial velocity map is remarkably similar to that of Katz et al. (2018) and in the simulation traces tightly wound spirals. The bridge between...
Figure 1. Surface density evolution of the Galactic disc during the last stage of the Sgr impact on the disc. The last two pericentric passages of Sgr occur at $t \sim -0.5$ Gyr and $t \sim 0.0$ Gyr which seed the formation of a strong bi-symmetric spiral as well as fast bar with pattern speed $\Omega = \omega/m \sim 65$ km/s/kpc. Sgr’s present-day position in the L2 model is reached at $t \sim 0.38$ Gyr but due to the uncertainty in the orbital period of Sgr, we follow the response of the disc for another $\Delta t \sim 0.5$ Gyr window.

the positive velocity arcs at $(X,Y) = (-12,2)$, also seen in [Katz et al. 2018] in fact marks a remaining inlet of high-density in the disc. The orientation is also strikingly similar.

The corresponding vertical velocity map in the Gaia-like region in the top-middle panel of Figure 2 also traces a warp as noticed in [Katz et al. 2018] and [Poggio et al. 2018], with amplitude variations that are not too far off from the data in the range $-5 < V_Z/\text{km s}^{-1} < 5$. However, this interpretation while reasonable, needs to be tempered by the fact that this does not correspond to a warp as generally been advocated in the observations of the HI neutral gas ([Levine et al. 2006]). Zooming out, we notice that this is only about half of the bigger picture. Indeed, during its interaction, Sgr excites vertical density waves in the disc which propagate outward ([Gómez et al. 2013] Laporte et al. 2018b) with physical wavelengths varying from 5 to 10 kpc. It is expected that beyond a Galactocentric radius of $\sim 15$ kpc, a dip in $V_Z$ should arise which would be a clear signature of a bending wave in the disc. We thus caution that a much larger volume will need to be probed in order to gain a more observationally complete consensus on the structure of the Galaxy. This should in principle be testable through the numerous upcoming spectroscopic campaigns in both hemispheres with APOGEE, DESI, WEAVE and 4MOST.

The simulated median azimuthal velocity map in the top right panel of Figure 2 also reveals a qualitatively similar behaviour to that seen in the Gaia data [Katz et al. 2018] with a decrease from 240 to 200 km/s as one moves in the direction of the Anticenter within the region probed by the data.

In this section, we have linked the formation of this velocity field in $V_R, V_Z, V_\phi$ to the last pericentric passage of Sgr. During this time, the dwarf excites a bi-symmetric spiral (and a fast bar) which tightly winds up after 0.7 Gyr until it gives rise to a velocity field with qualitatively similar features to the Gaia probed volume. Interestingly, this timescale, $\Delta t \sim 0.7$ Gyr, is also consistent with different models for the last pericentric passage [Niederste-Ostholt et al. 2012] [Dierickx & Loeb 2017] [Laporte et al. 2018b] which situate it between 0.4 – 1 Gyr. Thus it is tempting to link the present-day structure of the disc to it reacting to Sgr’s last pericentric passage.

Whether the spiral patterns seen in the data have a solely internal origin due to intrinsic disc instabilities remains an open possibility. However, together with the signs of vertical oscillations in the disc ([ Widrow et al. 2012] Antoja et al. 2018) it is likely that the impacts of Sgr on the disc played a role in setting the structural/kinematical asymmetries of the disc in both the radial and vertical direction.

Nonetheless, we note that a striking resemblance to the signal in the [Katz et al. 2018] maps can be reproduced in the interaction scenario producing tightly wound spiral structure. This is in agreement with [Quillen et al. 2018], who linked low-velocity moving groups in the $U-V$ plane to tightly wound spirals.

4 SUBSTRUCTURE IN THE SOLAR VICINITY

In this section we inspect the structures imparted on the disc after its interaction with Sgr in the last phases of its evolution inside solar-neighborhood-like (SN) volumes. As a starting point, we choose purposefully, the same snapshot for which we found a match in the velocity structures in the midplane in section 3. We place ourselves in a SN-like region at $(X,Y) = (-8,0)$. Given the modest number of particles used in the disc ($N_{\text{disc}} = 5 \times 16^3$), we choose a region bounded by $R_{\text{helio}} < 3.0$ and $160^\circ < \phi < 280^\circ$. We caution that these cuts are somewhat larger than the
Figure 2. Top panels: 2D $V_R$, $V_Z$, $V_\phi$ maps in the left, middle and right panels respectively, with density contours overlaid (grayscale lines). The square region corresponds to a spatial section similar to that in Katz et al. (2018) and Poggio et al. (2018). The reported velocity pattern from spiral arms can be clearly seen, albeit with differing amplitudes but with similar wavelengths to the observations. The disc is also warped in a similar orientation to the data. Bottom panels: 2D Surface density contours, median $Z$ and $\sigma Z$ maps in the the left, middle and right panels respectively. The magenta lines mark the lines of 30, 40 degrees respectively along which the bar is aligned. The disc shows both signs of flaring and warping (as expected from the complementary $V_Z$ map in the top middle panel).

4.1 The phase-space spiral pattern

In Figure 3, we examine the $V_Z - Z$ plane colored by density (left), $V_r$ (middle), and $V_{\phi}$ (right) and find a pattern strikingly similar to those observed by Antoja et al. (2018). This is the first time this is presented in a full N-body simulation of the impact of Sgr with the Milky Way, which did not resort to ad-hoc initial conditions of putative perturbations (Binney & Schoenrich 2018, e.g.). While the amplitudes of the vertical perturbations are larger by a factor of two compared to the observations, the qualitative match to both the $V_R(V_Z, Z)$ and $V_\phi(V_z, Z)$ maps (middle and right panels) is noteworthy and remarkable. The snail shell in the density requires more imagination to see, probably due to the large spatial volume used and low particle numbers. Indeed, thanks to the coupled motions in non-separable potentials, the spirals become much more easily identifiable in the space of $V_R(V_r, Z)$ or $V_\phi(V_z, Z)$ (Binney & Schoenrich 2018, Darling & Widrow 2018).

To understand the origin of this structure, it is useful to consider the evolution of the Galactic disc with respect to the last pericentric passage of Sgr in its last phase of disruption. In Figure 4, we show a time series of the mean vertical velocity of the disc. We note that as Sgr hits the disc, it excites vertical density waves throughout the whole disc, which are maintained on Gyr timescales. One can discern by eye the local impacts of Sgr during each pericentric passages which give local velocity kicks of a few 10s of km/s but also set new generations of bending waves for which the disc is globally perturbed as seen in the snapshot $\sim 100$ Myr after the last pericentric passage. The latter phenomenon is unique to self-gravitating discs and missed in toy models of phase-mixing (Minchev et al. 2009, Antoja et al. 2018, Binney & Schoenrich 2018).

In Figure 5, we follow the formation of this structure in $V_R(Z, V_Z)$ back in time all the way back to the time prior to the last pericentric passage. Given that the impact with Sgr creates vertical density perturbation for which the whole disc is participating, we just focus on a volume centered at $(X, Y) = (-8, 0)$ tracking the snail pattern back in time up to just before the last impact.

The latest perturbation clearly dominates over previous ones which re-sets a snail-like pattern (see second map in top panel of Figure 4) which grows in time wrapping over itself until it goes through two tight consecutive wraps. A similar pattern is also seen in the $V_\phi(Z, V_Z)$ plane in Figure 6.

The phase-mixing timescale, ultimately depends on the structure of the MW potential, the strength of the impact, but the number of tightly wound wraps may be used to give

\[^2\] We have also tried following the individual particles making up the snail pattern, and found that our results did not vary so much.
Figure 3. Phase-space spiral in a solar neighbourhood-like region in the disc following after the impact with Sgr at \( t = 0.8 \) Gyr. Left: \( \rho(Z,V_Z) \) map. Middle: \( V_\phi(Z,V_Z) \) snail pattern showing \( \sim 2 \) wraps. Right: \( V_R(Z,V_Z) \) map showing two consecutive wraps. These maps are in qualitative agreement with those observed in the real data. These are first such maps reproduced by an N-body simulation of the Sgr dwarf impacting the disc. Disagreements on the quantitative side lie in the amplitude of the spiral pattern which is larger by a factor of \( \approx 2 \).

Figure 4. Evolution of the mean vertical velocity of the disc with respect to the last pericentric passage of Sgr. Tidal impulses from last two pericentric passages are highlighted at \( t = -0.5 \) Gyr and \( t = 0.0 \) Gyr respectively. These passages maintain the generation of new vertical density perturbations showing that the disc response is global and not just local.

Figure 5. Time evolution of the snail phase-mixing pattern in the disc. The onset of the spiral is set during Sgr’s last last pericentric passage at \( t \sim 0.0 \) and persists for \( \Delta t \sim 0.4 - 0.8 \) Gyr during which the pattern winds itself further due to phase-mixing.
a constraint on the time of the impact (Antoja et al. 2018). The Gaia data seems to see two consecutive wraps. This is also the case in our numerical experiments, for which we can trace the origin of the snail back to the time of the last impact with the Sgr dSph and trace two wraps in $V_\phi (V_z, Z)$ and $V_R (V_z, Z)$ at $\Delta t \sim 0.4 - 0.8$ Gyr past the last pericentric passage. This is consistent with the values derived by Antoja et al. [2018].

However, this seems a priori at odds with the separation of arches in the v-φ plane by 20 km/s, which would correspond to a perturbation 1.9 Gyr ago according to the models of Minchev et al. [2009]. On the other hand, given that Sgr impacts the disc multiple times in its lifetime, it could be that because of the longer orbital periods in the radial direction, phase-mixing does not wash away these fine structures as fast as in the vertical direction.

We conclude that the Sgr may be the culprit behind the origin of the snail. This is the first time recorded in a N-body simulation of the Sgr dwarf spheroidal impact with the Milky Way. It demonstrates that the effect of the Sgr dwarf galaxy in setting up perturbations in the disc from its outer edge (through the excitation of the MW dark matter halo wake) to its inner-most region (through its tides) may be more important than previously appreciated (or ignored). More work will be necessary to be carried out with adapted simulations to properly model the orbit of the dwarf through careful stream fitting and varying initial conditions for the structure of the Galactic to assess the ranges of outcomes whether a quantitative agreement may be achieved, as we stress that these matches are only qualitative for the moment. The role of the LMC would also complicate modeling efforts (Gómez et al. [2016], Laporte et al. [2018a,b]) as well as dark subhalos (Feldmann & Spolyar 2015). However, given that the models are successful in reproducing many structures in the outer disc and even locally, this is rather encouraging.

Given the remarkable qualitative match between the simulated velocity fields and phase-space spirals with the data, this may after all be within reach especially given the very modest ($N_{\text{disc}} \sim 5 \times 10^6$) number of particles used in our N-body experiments.

4.2 Ridges in the $V_\phi - R$ plane

Using the same simulation time output for which we have identified a matching snail-shell pattern and median velocity fields we look at the structure of the $V_\phi - R$ ridges (Figure 7). We note a striking resemblance to the Gaia DR2 data, which is not reproduced as well in the transient spiral models of Hunt et al. [2018]. Nonetheless, given that we only consider one fiducial MW model, it might be worthwhile to study the evolution in isolation of different MW models to see whether the form of the ridges can be reproduced by impact models or be mimicked by internal instabilities, or the combination of the two. We leave the interpretation of these structures to a future study.

4.3 Spatially asymmetric substructures in the $V_\phi - V_R$ & $V_\phi - V_z$ planes

It is also interesting to ask whether some of the moving groups identified in the $U - V$ plane are asymmetric about the midplane. Recently, it has been suggested that the moving group Coma-Berenices may have been excited by the vertical perturbations from Sagittarius (Monari et al. [2018]).

In this section we explicitly choose a different snapshots to the previous sections, so the features presented here do not coincide with those presented earlier. This is because the morphology of the $U - V / U - W$ planes are sensitive to the location of the solar-neighbourhood-like volume and the

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3 Upon finishing writing this paper Binney & Schoenrich [2018] presented a re-evaluation of the data and derived a lower timescale for the snail pattern of $t_{\text{snail}} \sim 0.2 - 0.4$ Gyr which brackets our predicted N-body simulation values from the impact of Sgr with those from Antoja et al. [2018].
probability of coincidentally reproducing the same moving groups features as seen in the Gaia data is highly improbable, since the simulations are not tuned to this effect.

In Figure 8, we look for such Coma Berenices analogues of asymmetric moving groups and identify such an instance at $t = 0.4$ Gyr. We notice the existence of a moving group with $V_0 \sim 300$ km/s which is clearly visible. Arguably, the structure and bulk motion of the moving group is not identical to Coma Berenices in shape or velocity, but it should be appreciated that this structure is reminiscent of the Galactic disc and is only present on one side of the midplane. Indeed, as Sgr orbits around the Galaxy, it excites multiple generations of vertical density waves which propagate to the outer disc (Gómez et al. 2013; Laporte et al. 2018b). This can be also seen in Figure 4. More generally, neglecting the self-gravity of the disc, as a result of the perturbations (through DM halo wake and tides from the Sgr dSph body), stars are expected to be simultaneously excited moving on new orbits which then undergo phase-mixing (de la Vega et al. 2015). This holds remarkably well in the outer disc where the self-gravity is negligible and where disc perturbations seeded by Sgr are able to produce ACS/EBS-like stream structures (“feathers”) (Laporte et al. 2018c). It could be that Coma Berenices may be part of the end of a disc stream crossing the solar-neighbourhood, in contrast to an accreted stream from a disrupted satellite. A chemical characterisation of Coma Berenices through a cross-match with the GALAH/RAVE surveys should in principle uncover the nature of this moving group as an accreted stream or a disc component.

5 DISCUSSION

Only a few models considering the self-gravitating response of the disc to the Sgr dSph exist (Purcell et al. 2011; Gómez et al. 2013; Laporte et al. 2018a) and quantitative successes have only recently been achieved in the latest experiments of (Laporte et al. 2018b) which considered more realistic initial conditions in order to explain the origin of outer disc overdensities, thin stellar streams towards the Anticenter (Laporte et al. 2018c) while satisfying pre-Gaia constraints on disc asymmetries in the solar neighbourhood (Widrow et al. 2011).

All these past experiments considered a fiducial disc model to study the response of a disc to radial and vertical density perturbations without exploring how this would vary for different disc distribution function. In this regard, the range of possibilities of outcomes on the amplitude of the fluctuations in the radial and vertical directions are somewhat restricted, leaving room for additional complex phenomenology. We leave this to future studies. For now, we note that many features revealed in the Gaia data can be qualitatively reproduced by a model of the Milky Way disc interacting with the Sgr dSph and that the structure of the velocity field and the final morphology of the disc points to a close link between the interaction of the Milky Way with its most recently almost engulfed massive satellite galaxy.

This clearly highlights to the importance of the role of Sgr in exciting many disequilibrium features in the Milky Way. We also note, that dark subhalos have been proposed to excite vertical density waves (Widrow et al. 2013; Feldmann & Spolyar 2015; Chequers & Widrow 2017), but their amplitudes are much lower. Adding to this, signs of vertical breathing and bending wave-like structure can also be “mimicked” as a consequence of phase-mixing after a merger perturbation, as shown by de la Vega et al. (2015) using test particle simulations in order to exclude self-gravitating response of the disc. More detailed studies isolating these effects would be warranted but are beyond the scope of this current contribution.

In Laporte et al. (2018b), we argued that because of the different timescales present in the Galactic disc, the outer disc structures of the Milky Way together with those in the inner-Galaxy may probe different “time regimes” of the orbital mass-loss history of Sagittarius. The existence of the phase-space spiral (Antoja et al. 2018) and excitation of tidal tails of the Milky Way (Laporte et al. 2018c) in the outer disc may very well probe different events from a few 100 Myr to Gyrs. By combining the constraints at different Galactocentric radii, we may hope to be able to both uncover the origin of various non-axisymmetries and their relation to the interaction history of the Milky Way with Sgr in the last $\sim 5$ Gyrs.

6 SUMMARY & CONCLUSION

Many of the signs of perturbations in the Milky Way such as the vertical disturbances in the MW within the solar neighbourhood, the spiral patterns in the solar vicinity, ridges in $V_0 - R$, the Monoceros Ring and other overdensities such as EBS, ACS and TriAnd can all be understood as part of the interaction of the disc with the Sgr dwarf galaxy, with the condition that the progenitor was more massive than previously assumed. In summary, we show that:

$Q > 2$ everywhere because we were interested in studying the response of a disc which did not develop a bar or spiral arms through internal instabilities when evolved in isolation, for ease of interpretation. We caution that this was a purely numerical choice.
Figure 8. $V_\varphi - V_R$, $V_\varphi - V_Z$ planes for stars selected in a solar neighbourhood-like region (right panels). We also make the distinction between these planes above the midplane and below it (left and middle panels respectively).

(i) The Milky Way subjected to an interaction with Sgr shows signs of ongoing phase-mixing around the Sun, with patterns qualitatively similar to those recently observed in the Gaia DR2 data [Antoja et al. 2018]. The disagreements are only within a factor of two, leaving room for more detailed exploration.

(ii) The $U - V$, $U - W$ planes show a rich array of substructures similar to the data, excited as a result of this interaction, such as asymmetric moving groups like Coma Berenices.

(iii) Ridges similar to [Antoja et al. 2018] are produced continuously by spiral arms excited and rings by the interaction with Sgr throughout the evolution of the Milky Way. The current pattern seen today in $V_\varphi - R$ closely matches the ones in the models, suggesting a close link between the excitation of spiral arms with the orbital mass loss history of the Sgr dSph.

(iv) The velocity fields seen in the DR2 data as in [Katz et al. 2018] can be reproduced qualitatively by an interaction of Sgr with the Milky Way disc. However, the amplitudes in the models considered are too large notably in $V_R$. This may be related to the orbital mass loss history of Sgr (which would affect the resulting tides acting on the Galactic disc) and/or the underlying disc model assumed for the MW.

We note that [Purcell et al. 2011] argued that the Sgr dSph could be an architect of spiral structure in the Milky Way. At the time, not many constraints around the Sun were available. From our new models, we conclude that the Sgr dwarf spheroidal may be more closely linked to the disc than previously thought, generating the outer disc structures [La- porte et al. 2018] all the way to shaping the central part of the Galaxy and the phase-space structure around the the Sun as revealed by the Gaia satellite.

We showed that the impact of Sgr may be able to explain the origins of many different non-equilibrium features. Matching the amplitudes of the signals will be challenging but our simulations already show some quantitative matches which are not too far off, making further exploration a worthwhile pursuit.

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REFERENCES

Antoja T., Helmi A., Romero-Gómez M., Katz D., Babusiaux C., Drimmel R., Evans D. W., Figueras F., Poggio E., Reyle C., Robin A. C., Seabroke G., Soubiran C., 2018, ArXiv e-prints
Bailin J., 2004, PhD thesis, The University of Arizona, Arizona, USA
Bergemann M., Sesar B., Cohen J. G., Serenelli A. M., Sheffield A., Li T. S., Casagrande L., Johnston K. V., Laporte C. F. P., Price-Whelan A. M., Schoenrich R., Gould A., 2018, ArXiv e-prints
Besla G., Kallivayalil N., Hernquist L., Robertson B., Cox T. J., van der Marel R. P., Alcock C., 2007, ApJ, 668, 949
Binney J., Schoenrich R., 2018, ArXiv e-prints
Blumenthal G. R., Faber S. M., Flores R., Primack J. R., 1986, ApJ, 301, 27
Carlin J. L., DeLaunay J., Newberg H. J., Deng L., Gómez F. A., White S. D. M., Marinacci F., Slater C. T., Gao L., et al. 2008, MNRAS, 387, 536
Crane J. D., Majewski S. R., Rocha-Pinto H. J., Frinchaboy P. M., 2018, MNRAS, 473, 228
Darling K., Widrow L. M., 2018, ArXiv e-prints
de la Vega A., Quillen A. C., Carlin J. L., Chakrabarti S., 2015, MNRAS, 454, 933
Deason A. J., Belokurov V., Koposov S. E., 2018, MNRAS, 473, 4248
Dwarf G., 2018, ArXiv e-prints
Dold A., 1999, AJ, 118, 900
Dierickx M. I. P., Loeb A., 2017, ApJ, 836, 92
Drimmel R., 2000, AAP, 358, L13
Dehnen W., 2000, AJ, 119, 800
Dehnen W., 2000, AAP, 358, L13
Dong H., Zhao G., Zhao Y., 2013, ApJL, 777, L5
Chequers M. H., Widrow L. M., 2017, ArXiv e-prints
Crank J. D., Majewski S. R., Rocha-Pinto H. J., Frinchaboy P. M., Skrutskie M. F., Law D. R., 2003, ApJL, 594, L119
Darling K., Widrow L. M., 2018, ArXiv e-prints
de Boer T. J. L., Belokurov V., Koposov S. E., 2017, ArXiv e-prints
de la Vega A., Quillen A. C., Carlin J. L., Chakrabarti S., D’Onghia E., 2017, MNRAS, 473, 4248
Dennin W., 1998, AJ, 115, 2384
Dennin W., 2000, AJ, 119, 800
Dierickx M. I. P., Loeb A., 2017, ApJ, 836, 92
Drimmel R., 2000, AAP, 358, L13
Eggen O. J., 1969, PASP, 81, 553
Feast M. W., Menzies J. W., Matsunaga N., Whitelock E., 2013, MNRAS, 429, 159
Gómez F. A., Minchev I., O’Shea B. W., Beers T. C., Bullock J. S., Purcell C. W., 2013, MNRAS, 429, 159
Gómez F. A., Minchev I., O’Shea B. W., Beers T. C., Bullock J. S., Purcell C. W., Villalobos A., 2012, MNRAS, 423, 3727
Gómez F. A., Minchev I., Villalobos Á., O’Shea B. W., Williams M. E. K., 2012, MNRAS, 419, 2163
Gómez F. A., White S. D. M., Marinacci F., Slater C. T., Grand R. J. J., Springel V., Pakmor R., 2016, MNRAS, 456, 2779
Grillmair C. J., 2006, ApJL, 651, L29
Hunt J. A. S., Hong J., Bovy J., Kawata D., Grand R. J. J., 2018, ArXiv e-prints
Hunter C., Toomey A., 1969, ApJ, 155, 747
Ibata R. A., Gilmore G., Irwin M. J., 1994, Nature, 370, 194
Ibata R. A., Razoumov A. O., 1998, AAP, 336, 130
Katz D., Antoja T., Romero-Gómez M., Drimmel R., Reylé C., Seabroke G. M., Soubiran C., Babusiaux C., Drimmel R., Figueras F., Poggio E., Robin A. C., Evans D. W., Gaia Collaboration 2018, ArXiv e-prints
Laporte C. F. P., Gómez F. A., Besla G., Johnston K. V., Garavito-Camargo N., 2018, MNRAS, 473, 1218
Laporte C. F. P., Johnston K. V., Gómez F. A., Garavito-Camargo N., Besla G., 2018, MNRAS
Laporte C. F. P., Johnston K. V., Tzanidakis A., 2018, ArXiv e-prints
Levine E. S., Blitz L., Heiles C., 2006, ApJ, 643, 881
Li T. S., Sheffield A. A., Johnston K. V., Marshall J. L., Majewski S. R., Price-Whelan A. M., Danke G. J., Beaton R. L., Bernard E. J., Richardson W., Sharma S., 2017, ApJ, 844, 74
Ludlow A. D., Navarro J. F., Angulo R. E., Boylan-Kolchin M., Springel V., Frenk C., White S. D. M., 2014, MNRAS, 441, 378
Majewski S. R., Skrutskie M. F., Weinberg M. D., Ostheimer J. C., 2003, ApJ, 599, 1082
Martin N. F., Ibata R. A., Irwin M., 2007, ApJL, 668, L123
Martin N. F., Ibata R. A., Rich R. M., Collins M. L. M., Fardal M. A., Irwin M. J., Lewis G. F., McConnachie A. W., Babul A., 2014, ApJ, 787, 19
Minchev I., Nordhaus J., Quillen A. C., 2007, ApJL, 664, L31
Minchev I., Quillen A. C., Williams M., Freeman K. C., Nordhaus J., Siebert A.,Bienaymé O., 2009, MNRAS, 396, L56
Monari G., Famaey B., Minchev I., Antoja T., Bienaymé 2018, Research Notes of the American Astronomical Society, 2, 32
Newberg H. J., Yanny B., Rockosi C., Grebel E. K., Rix H.-W., Brinkmann J., Csabai I., Hennessy G., Hindsley R. B., Ibata R., Ivezić Ž., Lamb D., Nash E. T., Odenkirchen M., Rave H. A., Schneider D. P., Smith J. A., Stolte A., York D. G., 2002, ApJ, 569, 245
Niederste-Ostholt M., Belokurov V., Evans N. W., 2012, MNRAS, 422, 207
Poggio E., Drimmel R., Lattanzi M. G., Smart R. L., Spagna A., Andrae R., Bailer-Jones C. A. L., Fouesneau M., Antoja T., Babusiaux C., Evans D. W., Figueras F., Katz D., Reylé C., Robin A. C., Romero-Gómez M., Seabroke G. M., 2018, ArXiv e-prints
Price-Whelan A. M., Johnston K. V., Sheffield A. A., Johnston K. V., Sesar B., 2018, ArXiv e-prints
Price-Whelan A. M., Johnston K. V., Drill K., 2018, ArXiv e-prints
Purcell C. W., Bullock J. S., Tollerud E. J., Rocha M., Chakrabarti S., 2011, Nature, 477, 301
Quillen A. C., De Silva G., Sharma S., Hayden M., Freeman K., Bland-Hawthorn J., Žerjal M., Asplund M., 2018, MNRAS, 478, 228
Quillen A. C., Minchev I., Bland-Hawthorn J., Haywood M., 2009, MNRAS, 397, 1599
Reid M. J., Menten K. M., Brunthaler A., Zheng X. W., Dame T. M., Xu Y., Wu Y., Zhang B., Sanna A., Sato M., Hachisuka K., Choi Y. K., Immer K., Moscadelli L.,
Footprints of the Sagittarius dwarf spheroidal in the Galaxy

Rygl K. L. J., Bartkiewicz A., 2014, ApJ, 783, 130
Schuster W. J., Moitinho A., Márquez A., Parrao L., Covarribias E., 2006, AAP, 445, 939
Sharma S., Johnston K. V., Majewski S. R., Muñoz R. R., Carlberg J. K., Bullock J., 2010, ApJ, 722, 750
Sheffield A. A., Price-Whelan A. M., Tzanidakis A., Johnston K. V., Laporte C. F. P., Sesar B., 2018, ApJ, 854, 47
Weinberg M. D., 1989, MNRAS, 239, 549
Weinberg M. D., 1998, MNRAS, 299, 499
Widrow L. M., Barber J., Chequers M. H., Cheng E., 2014, MNRAS, 440, 1971
Widrow L. M., Gardner S., Yanny B., Dodelson S., Chen H.-Y., 2012, ApJL, 750, L41
Williams M. E. K., Steinmetz M., Binney J., Siebert A., Enke H., Famaey B., Minchev I., de Jong R. S., Boeche C., Freeman K. C., Bienaymé 2013, MNRAS, 436, 101
Xu Y., Newberg H. J., Carlin J. L., Liu C., Deng L., Li J., Schönrich R., Yanny B., 2015, ApJ, 801, 105