Signatures of minor mergers in the Milky Way disc – I. The SEGUE stellar sample

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ABSTRACT

It is now known that minor mergers are capable of creating structure in the phase-space distribution of their host galaxy’s disc. In order to search for such imprints in the Milky Way, we analyse the Sloan Extension for Galactic Understanding and Exploration (SEGUE) F/G dwarf and the Schuster et al. stellar samples. We find similar features in these two completely independent stellar samples, consistent with the predictions of a Milky Way minor-merger event. We next apply the same analyses to high-resolution, idealized N-body simulations of the interaction between the Sagittarius dwarf galaxy and the Milky Way. The energy distributions of stellar particle samples in small spatial regions in the host disc reveal strong variations of structure with position. We find good matches to the observations for models with a mass of Sagittarius’ dark matter halo progenitor \( \lesssim 10^{11} \text{M}_\odot \). Thus, we show that this kind of analysis could be used to provide unprecedentedly tight constraints on Sagittarius’ orbital parameters, as well as place a lower limit on its mass.

Key words: methods: analytical – methods: data analysis – methods: numerical – Galaxy: disc – Galaxy: structure – galaxies: formation – galaxies: kinematics and dynamics.

1 INTRODUCTION

It is now widely accepted that the gravitational pull exerted by a merging satellite galaxy can generate structure in the stellar disc of its more massive host. A striking example of the outcome of these kind of interactions is the system composed of M51 and its companion galaxy, NGC 5195 (e.g. Oh et al. 2008; Dobbs et al. 2010). Previous studies have shown that prominent spiral structure is more commonly observed in galaxies located within groups or with companions (Kormendy & Norman 1979; Elmegreen & Elmegreen 1982, 1983). These observations highlighted the importance of tidal interactions on the structure of galactic discs. Although grand design spirals, such as the ones observed in M51, are related to massive companions (in this case, \( M_{M51}/M_{NGC 5195} \gtrsim 0.3 \)), several theoretical studies have shown that much less massive satellites can also create phase-space structure in galactic discs (Quinn, Hernquist & Fullagar 1993; Tutukov & Fedorova 2006; Kazantzidis et al. 2008; Villalobos & Helmi 2008; Younger et al. 2008; Minchev et al. 2009; Quillen et al. 2009; Bird, Kazantzidis & Weinberg 2012; Gómez et al., hereafter G12). Morphological features such as spiral arms, warps, flares, central bars and low surface brightness ring-like structures in the outskirts of a disc can be the result of either recent or ongoing accretion events.

Most of the previously mentioned morphological features have been observed in the disc of our own Galaxy (Newberg et al. 2002; Yanny et al. 2003; Levine, Blitz & Heiles 2006; Momany et al. 2006; Cabrera-Lavers et al. 2007; Pohl, Englmaier & Bissantz 2008).

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and various formation scenarios have been explored for most of them. An interesting example is the Monoceros ring, which is a
low-latitude stellar structure spanning about 180° in Galactic longitude at nearly constant Galactocentric distance. It has been
proposed that this structure could be the remnant of a tidally disrupted satellite galaxy (Helmi et al. 2003; Ibata et al. 2003; Conn et al. 2005; Pehar rubia et al. 2005). More recently, several authors have argued
that this dynamically cold ring could be the result of a tidal perturbation from a satellite galaxy on the Galactic disc (Kazantzidis et al. 2008; Younger et al. 2008; Quillen et al. 2009). In particular, the Sagittarius dwarf galaxy (Sgr) has been proposed as a possible perturber of the Milky Way, causing the emergence of the Monoceros ring as the far extension of a Galactic spiral arm (Purcell et al. 2011, hereafter P11) and also potentially as a gravitational influence that circularized the orbit of a putative dwarf galaxy that could have been torn apart to become that same ring (Michel-Dansac et al. 2011). Motivated by recent studies on cosmological abundance matching (Conroy & Wechsler 2009; Behroozi, Conroy & Wechsler 2010), P11 considered models of Sagittarius with total masses as large as ∼10 per cent of the Milky Way’s mass. These models can successfully reproduce not only dynamically cold structures such as the Monoceros ring, but also other global morphological features observed in the Milky Way. However, its impact on the phase-space structure of the solar neighbourhood has not yet been explored.

As first shown by Minchev et al. (2009), the energy kick imparted by the gravitational potential of a satellite as it crosses the plane of the disc can strongly perturb the velocity field of disc stars located in local volumes such as the solar neighbourhood. In stellar samples close to the Sun (i.e. distances ≤0.2 kpcs), these perturbations can be observed in the u–v plane as arc-like features travelling in the direction of positive v, where u and v are the radial and tangential velocity components, respectively. In a follow-up study, G12 showed that the space defined by the energy and angular momentum of stars is a better choice than velocity space, as substructure remains visible even in much larger local volumes. Furthermore, they also showed that satellites with masses as small as 10 per cent of the mass of the host can leave imprints in the phase-space distribution of solar neighbourhood like volumes that could be identified as late as ≈5 Gyr after the first satellite’s pericentre passage. Substructure associated with this mechanism, known as ‘ringing’, is expected to be better defined in the Galactic thick disc. This is because these stars spend relatively little time near the Galactic plane, where perturbations from the Galactic bar, spiral structure and giant molecular clouds are more vigorous. Moreover, the thick disc is composed of a very old population of stars, with ages around 10–12 Gyr (Schuster et al. 2006; Bensby et al. 2007). Thus, most of its stars must have been in place at the time the hypothetical merger occurred.

An obvious question arises from our previous discussion: could a satellite galaxy like Sagittarius have left imprints of its tidal interaction with the Milky Way’s thick disc in the local stellar phase-space distribution? Previous attempts to describe features in the velocity field of the solar neighbourhood have been primarily concerned with the dynamical effects induced by non-axisymmetric disc components, such as a central bar or self-gravitating spiral arms (see e.g. Dehnen 2000; Fux 2001; Minchev, Nordhaus & Quillen 2007; Minchev & Quillen 2008; Antoja et al. 2009, 2011; Minchev et al. 2010; Quillen et al. 2011). These studies have focused their attention on very small local volumes, dominated mostly by populations of thin-disc stars. However, little attention has been paid to the identification and characterization of substructure in local volumes of the Milky Way’s thick disc that may have originated as a response of the tidal interaction with a satellite galaxy (see e.g. Minchev et al. 2009).

In this work we attempt to fill this gap by analysing a full 6D phase-space catalogue of F/G-type dwarf stars from the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009). The great advantage of this catalogue, as presented by Lee et al. (2011b, hereafter L11), is that it contains accurate estimates of [α/Fe] and [Fe/H] ratios for a fraction of its stars. This enables a chemical separation of the disc system into likely thin- and thick-disc populations, avoiding unwanted biases associated with methods based on stellar kinematics or spatial distributions. To complement this analysis, we also explore the distribution of disc stars from the Schuster et al. (2006) catalogue.

The paper’s outline is as follows. Section 2 presents a brief review of the main properties of ringing. In Section 3 we describe the stellar samples analysed in this work. The distribution of stars in energy and angular momentum space of the F/G dwarf and the Schuster et al. (2006) catalogues are analysed in Sections 4 and 5, respectively. In Section 6 we apply the same analyses to high-resolution N-body simulations of the interaction between Sagittarius and the Milky Way. A summary and conclusions are presented in Section 7.

2 RINGING IN GALACTIC DISCS

Minchev et al. (2009), followed by G12, showed that relatively massive minor-merger events can generate substructure in the velocity field of disc stars located in the solar neighbourhood. Merging satellite galaxies with total masses as small as 10 per cent of the mass of the Milky Way may excite density waves whose signatures can be identified even 5 Gyr after the first satellite’s pericentre passage. The space of E–Lz is particularly well suited to identify density waves, since the waves are surfaces of constant energy (see also e.g. Helmi et al. 1999; Helmi & de Zeeuw 2000). Over time, these constant-energy features associated with the density waves become more closely spaced, and their number increases as a consequence of phase wrapping (see Section 3 of G12). In the top panel of Fig. 1 we show, in E–Lz space, the distribution of disc particles located within a 2.5-kpc sphere. The centre is at 8 kpc from the galactic centre and the distribution was obtained after 3.9 Gyr of evolution, which corresponds to a time since total disruption of the satellite galaxy of 1.9 Gyr. In this simulation, the satellite galaxy has a total initial mass equal to 20 per cent of the mass of the host. Note that only Npart = 976 are located within this 2.5-kpc sphere. It is clear that disc particles are distributed in different lumps of nearly constant energy, each of them associated with a different density-wave crossing the volume. The bottom panel of Fig. 1 shows a kernel histogram (KH) of energies, E. To compute the KH, a Gaussian kernel with bandwidth σ = 0.011ΔE was assigned to each particle. Here, ΔE = 4 × 10^4 km^2 s^-2 is approximately the total extent of the satellite in energy space within this volume. The KH is the sum of all of the Gaussian kernels. Since density waves are surfaces of nearly constant energy, they are observed in the KH as well-defined peaks. Note that larger values of σ tend to oversmooth the KH, erasing some of the peaks associated with substructure observed in E–Lz space. Conversely, smaller values produce noisier KHS. In what follows we keep the values of σ and ΔE fixed at these values.
3 THE STELLAR SAMPLES

3.1 The SEGUE F/G dwarf sample

The SEGUE F/G dwarf sample analysed in this work was culled from ∼70000 F- and G-type stars with available low-resolution spectroscopy (R ∼ 2000), as provided in Sloan Digital Sky Survey (SDSS) Data Release 8 (Aihara et al. 2011). Among them, about 63000 stars were targeted as G dwarfs; hence, our sample is dominated by the G dwarf candidates used by L11. The G dwarf candidates were obtained by selecting stars with colours and magnitudes in the range 0.48 < (g − r) < 0.55 and r0 < 20.2, respectively, while the rest of the sample covers 0.2 < (g − r) < 0.48 and q0 < 20.2. Thanks to this simple selection function, the stellar sample is expected to be completely unbiased with respect to kinematics, and only slightly biased towards metal-poor stars (see Schlesinger et al. 2011).

### 3.1.1 Local sample

In order to obtain a local sample of stars with accurate measurements of their 6D phase-space coordinates, as well as metallicities and [α/Fe] ratios, a series of cuts were applied to the complete catalogue. Here we provide a brief summary of the criteria used for the sample selection, but we refer the interested reader to L11 for a more detailed description of this procedure as we follow their prescription to select the final sample.

Stellar atmospheric parameters, such as effective temperature, $T_{\text{eff}}$, surface gravity, log g, and metallicity, [Fe/H], were determined using the SEGUE stellar parameter pipeline (SSPP; Allende Prieto et al. 2008; Lee et al. 2008a,b; Smolinski et al. 2011). In order to obtain high-quality estimates of both [Fe/H] and [α/Fe] (Lee et al. 2011a), only stars with spectra of signal-to-noise ratios greater than 30 Å$^{-1}$ were considered. Importantly, this also ensures that errors in the estimated radial velocities are smaller than 5 km s$^{-1}$. Proper motions were obtained following Munn et al. (2004), after correcting for the systematic error described in Munn et al. (2008).

Distances to individual stars were estimated using calibrated set of stellar isochrones (An et al. 2009a), following the prescription of An et al. (2009b). To minimize possible distance bias from stellar age effects near the main-sequence turn-off, only stars with log g ≥ 4.2 were considered. In addition, to minimize the errors on the estimates of phase-space coordinates, we only consider stars with distances from the Sun $0.4 < d < 2$ kpc. Note that the inner limit is imposed by the data themselves, due to saturation of the SDSS photometric scans for $g < 14.5$.

To compute Galactocentric positions and velocities of our local stellar sample, we assume the Sun to be located at $R_\odot = 8$ kpc, and that it has a peculiar velocity with respect to the local standard of rest (LSR) $(U, V, W)_\odot = (11.1, 12.2, 7.3)$ km s$^{-1}$ (Schrönherr, Binney & Dehnen 2010). We further assume a velocity of the LSR with respect to the Galactic Centre of $V_{\odot} = 220$ km s$^{-1}$. Finally, we discard stars with [Fe/H] ≤ −1.2 and $V_{\phi} < 0$ km s$^{-1}$ in order to avoid contamination (as much as possible) from the stellar halo, as well as the proposed metal-weak thick-disc component of the Galaxy (Carollo et al. 2010).

### 3.1.2 The thin- and thick-disc populations

As mentioned in Section 1, signatures of ringing are expected to be stronger in the thick disc than in the thin disc because its stars are less affected by perturbations from the Galactic bar, self-gravitating spiral arms and giant molecular clouds. More importantly, the thick disc is mainly composed of a very old stellar population, with ages of ∼10–12 Gyr (Schuster et al. 2006; Bensby et al. 2007). Thus, most of its stars must have been in place as recently as 5 Gyr ago – a required condition if, for example, we seek to identify signatures of a merger event that may have started approximately at that time.

Following L11, we split our local sample into likely thin- and thick-disc populations on the basis of their stellar chemical abundances, i.e. [α/Fe] and [Fe/H]. We assign stars to the thin-disc...
(low-[α/Fe]) and thick-disc (high-[α/Fe]) components according to the following scheme.

For stars with [Fe/H] ≥ −0.8,

(i) thin disc, if [α/Fe] < −0.08 × [Fe/H] + 0.15,
(ii) thick disc, if [α/Fe] > −0.08 × [Fe/H] + 0.25.

For stars with [Fe/H] < −0.8,

(i) thin disc, if [α/Fe] < +0.214,
(ii) thick disc, if [α/Fe] > +0.314.

While any old stellar population with high velocity dispersion would be suitable for our investigation, by assigning stars to the different components of the disc according to [α/Fe] we avoid introducing unwanted biases associated with methods based on stellar kinematics or spatial distributions. Note the gap of 0.1 dex left in the [α/Fe] cuts between the thin disc and thick disc, which is chosen to avoid misclassification of stars. For a detailed description of the motivation behind this scheme, we refer the reader to section 3.1 of L11.

3.2 The Schuster et al. (2006) sample

The Schuster et al. (2006, hereafter SCH06) catalogue comprises a total of 1533 high-velocity and metal-poor stars. Positions and proper motions for these stars were primarily derived from Hipparcos (Perryman et al. 1997), Tycho-2 (Høg et al. 2000) and the revised New Luyten Two Tenths (NLTT) catalogue (Salim & Gould 2003), whereas radial velocities were obtained from a number of different sources available in the literature (see SCH06, and references therein). As in Section 3.1, we compute Galactocentric velocities by assuming R⊙ = 8 kpc, (U, V, W)⊙ = (11.1, 12.2, 7.3) km s⁻¹ and VLSR = 220 km s⁻¹.

Metallicities estimated via a photometric calibration based on uvby-β photometry are also provided for the entire sample. As shown by SCH06, it is possible to discriminate stars from different Galactic components by means of the X parameter, where X is a simple linear combination of the rotational velocity and metallicity of the stars. Following SCH06, we discard from our sample all stars with X ≥ 0, in order to avoid potential contamination from the Galactic halo.¹

Note that estimates of [α/Fe] are not provided in the SCH06 catalogue. Thus, a subdivision between likely thin- and thick-disc stars cannot be performed following the scheme described in Section 3.1.2. Nevertheless, as shown by Nissen & Schuster (1991) and SCH06, the thin-disc population in this sample belongs to a very old disc component, with the bulk of the population older than 10 Gyr, and the remaining stars with ages between 10 and 4 Gyr. We thus ensure that most of these stars were already part of the disc ~5 Gyr ago. It is important to note that all disc stars in this sample are located at a distance from the Sun d < 0.2 kpc. Thus, this sample probes the innermost regions of the solar neighbourhood, complementing the more distant SDSS F/G dwarf sample.

4 THE SEGUE F/G DWARF SAMPLE IN E–Lc SPACE

We now analyse the E–Lc distribution of the stars present in our local SEGUE F/G dwarf sample. In order to obtain an estimate of the orbital energy of these stars we first need to assume a shape

| Disc | Bulge | Halo |
|------|-------|------|
| Md = 4 × 10¹⁰ | M_b = 8 × 10¹⁰ | M_c = 1 × 10¹² |
| r_a = 6.5 | r_e = 0.7 | r_e = 21.5 |
| r_b = 0.26 | c = 12 |

for the Galactic potential. We adopt a model consisting of three different components as follows.

(1) A Miyamoto–Nagai disc (Miyamoto & Nagai 1975):

\[ \Phi_{\text{disc}} = -\frac{GM_d}{\sqrt{R^2 + (r_a + \sqrt{Z^2 + r_b^2})^2}}. \]

(2) A Hernquist bulge (Hernquist 1990):

\[ \Phi_{\text{bulge}} = -\frac{GM_b}{r + r_e}. \]

(3) A NFW dark matter (DM) halo (Navarro, Frenk & White 1996):

\[ \Phi_{\text{halo}} = -\frac{GM_c}{r \left( \log(1 + c) - c/(1 + c) \right) \log \left( 1 + \frac{r}{r_e} \right)}. \]

Table 1 summarizes the numerical values of the parameters used for our Galactic potential model. These parameters are similar to those used by other authors (e.g. Bullock & Johnston 2005; Gómez et al. 2010; Peñarrubia et al. 2010) and fit the Milky Way rotation curve (Klypin, Zhao & Somerville 2002). Note that, as described by Gómez & Helmi (2010, and references therein), the results are not strongly dependent on the particular choice of the potential, since substructure in integrals of motion space are robust to small differences in the mass distribution because we always focus on small volumes in space. Hence, small changes in the potential essentially act as a zero-point offset, affecting all the stars present in this volume in the same way.

4.1 Thin disc versus thick disc

The top panel of Fig. 2 shows the distribution of α-enhanced, likely thick-disc stars in E–Lc space. For this figure we have only consid-
ered stars with d ≤ 2 kpc from the Sun and a total velocity error Vc = 20 km s⁻¹. As a result, and because of the different cuts applied to the complete catalogue (see Section 3.1), we are only left with a total of Nthick = 3141 likely thick-disc stars. A series of high-density features can be observed in this panel, especially at high values of E and Lc. These features become more evident in the KH of energies, shown as a red solid line in the bottom panel of the same figure. Comparison with Fig. 1 clearly indicates that, if these features are to be associated with ringing, they have a much smaller amplitude than might be expected. However, due to the relatively large threshold in total velocity errors considered (i.e. Vc < 20 km s⁻¹), these peaks may have been smoothed out; we explore this issue further in Section 4.2. On the other hand, due to the relatively low number of stars, some of the peaks may have arisen due to noise associated with poor sampling of the underlying distribution. To investigate this, we bootstrapped our thick-disc stellar subsample 2000 times and computed a KH for each one of the realizations. At each value of E, we sort the results of the KHS in ascending order. The shaded areas in the bottom panel of Fig. 2

¹ Note that only a fraction smaller than 3 per cent of our final F/G dwarf thick-disc subsample has X ≥ 0.
The bottom panel of Fig. 2 also shows (blue dashed line) the KH on $E$ of the stars associated with the low-$\alpha$, likely thin-disc stars. In this case, the total number of stars in the subsample is $N_{\text{thick}} = 3141$, and the thin-disc subsample comprises a population of stars that, at least locally, is less tightly bound than that of the thick disc. Note that, within volumes as small as the ones considered here, the Galactic potential can be regarded as constant. Thus, for these stars, the binding energy is mainly a function of their velocities. Since the thick disc is composed of a population of stars with a lag in $V_\phi$ of $\sim 30$ km s$^{-1}$ relative to the thin disc (as shown in e.g. L11), it is not surprising to find that these stars have a larger binding energy. It is also noticeable that the thick-disc stars exhibit a much broader distribution in energy than their thin-disc counterparts. This is a manifestation of the larger velocity dispersion (in all directions) associated with the thick-disc component. Finally, note that the thin disc exhibits a much smoother distribution when compared to that of the thick disc. One has to bear in mind that the thin-disc subsample is also $\sim 35$ per cent larger than the thick-disc subsample. Thus, noise associated with poor sampling is reduced. This is indicated by the tighter blue and light blue shaded regions, computed as discussed above. Nevertheless, in Section 4.2 we show that this result holds even when considering smaller stellar subsamples with more accurately determined velocities.

4.2 Characterizing the effects of errors on phase-space coordinates

As noted above, the measurement errors in the phase-space coordinates of our local F/G dwarf stellar sample may be large enough to either smooth out or erase some of the signatures of ringing in $E-L_z$ space. To characterize their effect on the observed features in the KHS, we have extracted the distributions of errors from our thick-disc subsample, and convolved them with the position and velocities of the particles shown in Fig. 1. Estimates of the errors were obtained from the SSPS (see L11 and references therein); their distributions are shown in Fig. 3. The left-hand panel of Fig. 4 shows the results of this convolution when errors in velocities as large as 20 km s$^{-1}$ are considered. The red solid line shows the averaged KH of normalized energies, $E_{\text{norm}}$, obtained after 400 different realizations of the error convolution, whereas the shaded region indicates its standard deviation. Here, $E_{\text{norm}} = [E - \min (E)]/\Delta E$, with $\Delta E$ defined as in Section 2. It is important to remark that, to compute the energies of the N-body particles after convolution with errors, we have used the same analytic potential that was used for the F/G dwarf sample. Note that this simulation was designed to emulate the result of a minor merger experienced by a Milky Way-like galaxy at $z = 1$. Thus, the properties of this potential were scaled to those expected at $z = 1$, as described in Section 2 of G12. Interestingly, due to the large magnitude of the errors considered, most of the structure associated with ringing has been erased. Furthermore, some spurious peaks can be observed. For comparison, we show with a black dashed line the KH obtained from this set of particles before error convolution. The middle panel of this figure shows the results of the same procedure, now after convolving with errors in velocity $V_{\text{err}} < 16$ km s$^{-1}$. Note that these errors are still large enough to erase most of the signatures of ringing. Only when

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Figure 2. Top panel: $E-L_z$ distribution of likely thick-disc stars located within 2 kpc of the Sun, obtained from our F/G dwarf sample. The different colours (contours) indicate different number of stars. Only stars with total errors in velocity $V_{\text{err}} < 20$ km s$^{-1}$ are considered. The subsample contains $N_{\text{thick}} = 3141$ high-$[\alpha/\text{Fe}]$ stars. Note the presence of a series of high-density features, especially at large values of energies. Bottom panel: KH of $E$, obtained from both the thick-disc (red solid line) and the thin-disc (blue dashed line) stellar subsamples. The thin-disc subsample contains $N_{\text{thin}} = 4903$ low-$[\alpha/\text{Fe}]$ stars. The shaded areas indicate errors associated with poor sampling of the underlying distributions (see text). The high-density features observed in the top panel correspond to peaks in the KH. Note that the thin-disc subsample exhibits a smoother distribution relative to the thick disc.

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show the 25th–75th percentiles (light shadow) and the 5th–95th percentiles (dark shadow) of the distribution of values obtained from the bootstrapped KHS. The results of this procedure indicate that only a few of these peaks have amplitudes with values above the noise level. However, in the following sections we show that, after accounting for the effects of measurement errors, and through exploration of the SCH06 catalogue, some of the remaining peaks may indeed be real.
considering errors in velocity $V_{\text{err}} < 11 \text{ km s}^{-1}$ (right-hand panel) do we start recovering the previously observed peaks.

This exercise clearly indicates that, in order to detect signatures of ringing in the Milky Way disc, very accurate 6D phase-space catalogues must be explored. A highly accurate subset of stars can be obtained from our local F/G dwarf sample, at the expense of significantly reducing the total number of stars analysed. The top panel of Fig. 5 shows the KHzs of the thick disc (red solid line) and the thin disc (blue dashed line) obtained when only stars with total velocity errors $V_{\text{err}} < 11 \text{ km s}^{-1}$ are considered. As a result of this more restrictive cut, we are left with $N^\text{thick}_{\text{stars}} = 968$ thick-disc stars and $N^\text{thin}_{\text{stars}} = 1132$ thin-disc stars. Interestingly, not only do we recover most of the features already observed in Fig. 2, but we also find that the structure here is more sharply defined (as expected from our previous discussion). Note, however, that errors associated with poor sampling of the underlying distribution are larger due to the smaller number of stars. This is evident by the wider areas covered by the shaded regions, obtained from the bootstrap analysis of our subsample (see Section 4.1). Nevertheless, it is important to note that the number of thick-disc stars in this more accurate subsample, $N^\text{thick}_{\text{stars}}$, is approximately equal to the number of particles analysed in the $N$-body model, $N^\text{model}_{\text{part}}$, shown in Figs 1 and 4.

Alternately, it is possible to obtain a more accurate subsample simply by analysing a much more local subset of stars. In the bottom panel of Fig. 5 we show the KH of $E$ obtained from a sample of stars with heliocentric distances projected on to the plane $R \leq 0.5 \text{ kpc}$. Note that by reducing the radius of our solar neighbourhood sphere we are constraining errors not only in the velocities of the stars, but also in their positions. After the cut we obtain a thick-disc subsample of $N^\text{thick}_{\text{stars}} = 2441$ stars, whereas the thin-disc subsample contains $N^\text{thin}_{\text{stars}} = 3021$ stars. Comparison with the top panels of Figs 5 and 2 shows again that many previously observed features are preserved. Furthermore, some of the features have become even more significant, in particular the peak located at $E \approx -0.97 \times 10^5 \text{ km}^2 \text{ s}^{-2}$. It is also interesting to note that, as previously discussed in Section 4.1, the thin-disc population exhibits a smoother energy distribution relative to that of the thick-disc population in both of these panels. Note that now both subsamples have comparable numbers of stars.
Signatures of mergers in the Galactic disc

Figure 5. Top panel: KHs of energies obtained from the SEGUE F/G dwarf thick disc (red solid line) and the thin disc (blue dashed line), when errors in total velocity smaller than 11 km s\(^{-1}\) are considered. The shaded regions indicate errors associated with poor sampling of the underlying distribution (see Section 4.1). Note that most of the previously observed features in Fig. 2 are more sharply defined, as expected from this more accurate subsample. Note also that the thin disc presents a smoother distribution in \(E\) with respect to the thick disc. Bottom panel: same as the top panel, but for stars located within \(R \leq 0.5\) kpc and total velocity errors smaller than 20 km s\(^{-1}\).

Figure 6. Top panel: KH of \(E\) obtained from the SCH06 sample of disc stars with total velocity error \(V_{\text{err}} < 11\) km s\(^{-1}\), shown with a black dashed line. The sample contains a total of 603 stars. Note the large number of peaks located at very similar values of \(E\) as in the KH of the F/G dwarf subsample, indicated with a red solid line. The slight shift between these two distributions can be accounted for by the different volumes probed by the samples (see text), as well as poor sampling of the underlying energy distribution. Bottom panel: same as the top panel, but for a sample of disc stars with total velocity error \(V_{\text{err}} < 20\) km s\(^{-1}\). This larger sample contains 813 stars. The coloured areas indicate the approximate energy range of the Arcturus stream (yellow), the Hercules stream (green) and the most significant peak identified in the SEGUE F/G dwarf sample (light blue).

5 THE SCHUSTER ET AL. (2006) SAMPLE IN \(E–L_z\) SPACE

The previously observed peaks in the KHs of our SEGUE F/G dwarf sample might be an indication of ringing in our own Galactic thick disc. However, due to the relatively small number of stars with the necessary small measurement errors, uncertainties associated with poor sampling of the underlying distribution are (for some features) still large. It is therefore important to look for additional evidence of ringing in other stellar catalogues already available in the literature. The SCH06 catalogue is particularly well-suited for this analysis, as it comprises a set of old and metal-poor disc stars (see Section 3.2). Furthermore, the disc stars in this sample are all located within \(d < 0.2\) kpc; thus they probe a region of the solar neighbourhood that is different from that explored by the more distant SEGUE F/G dwarf sample.

The black dashed line on the top panel of Fig. 6 shows the KH obtained from a subsample of likely disc stars from the SCH06 catalogue. Following our previous discussion, we first consider stars...
with total errors in velocities $V_{\text{err}} \leq 11 \text{ km s}^{-1}$. As a consequence, we are left with a total of 603 old disc stars. Interestingly, a large number of peaks can be observed, most of them located at values of $E$ consistent with those observed in the KH of F/G dwarf subsample, shown with a red solid line. As we explain in Section 6.2, due to the strong radial and azimuthal dependence on the location and amplitude of the peaks, together with the poor sampling of the underlying energy distribution, it is not surprising to find features in these KHs slightly shifted with respect to one another.

The bottom panel of Fig. 6 shows the KH from the SCH06 catalogue, obtained after considering stars with total velocity errors of $V_{\text{err}} \leq 20 \text{ km s}^{-1}$. This larger sample contains 813 stars. Again, note that many of the features observed in the KHs of both the SCH06 and the F/G dwarf samples are located at very similar values of $E$. The colour-coded areas in this panel indicate the approximate energy range in which the Arcturus and the Hercules moving groups are expected to be found. To compute these energy ranges, for simplicity, we have assumed the following for each moving group.

(i) A characteristic $V$ velocity component, $V_{\text{LSR}}$ (see e.g. Dehnen 1998; Fux 2001; Navarro, Helmi & Freeman 2004; Antoja et al. 2008; Klement, Fuchs & Rix 2008). Since this characteristic $V$ velocity is subject to relatively large uncertainties, to compute each energy range we assumed $V = V_{\text{LSR}} \pm 10 \text{ km s}^{-1}$.
(ii) A characteristic $U$ velocity component equal to zero.
(iii) A Galactocentric distance $R = 8 \text{ kpc}$.

The bottom panel shows that both moving groups could be associated with peaks in our KH. Note that, as previously explained in this section, it is not surprising to find slight shifts in the location of the peaks between the two analysed samples due to the different volumes probed. Minchev et al. 2009 considered the possibility that the Arcturus moving group is the result of a perturbation in the Galactic disc induced by a minor-merger event. They concluded that a minor merger that took place $\sim 1.9 \text{ Gyr}$ ago could explain not only the presence of the Arcturus moving group, but also other previously observed features in the local velocity field (see e.g. Arifianto & Fuchs 2006). It is important to note that streams with velocities larger than $V_{\text{LSR}} \sim \pm 50 \text{ km s}^{-1}$ are less likely to be related to the Galactic bar. Interestingly, the short time-scale associated with this event is consistent with the estimated age of the Galactic bar, as measured by Cole & Weinberg (2002) ($\sim 3 \text{ Gyr}$ ago). This suggests that the same event that could have caused the formation of the Galactic bar could have also left the stellar disc unrelaxed, thus giving rise to the observed high-velocity stream. On the other hand, many studies have successfully described the presence of the Hercules moving group as a result of a resonant interaction with the bar (see e.g. Dehnen 2000; Minchev et al. 2007). However, as shown by Antoja et al. (2009, 2011), the effect that bars and spiral density waves have on the velocity field of galactic discs is highly degenerate. Therefore, the scenario in which the Hercules moving group was formed as the response of the Galactic disc to a minor-merger event cannot be ruled out.

6 THE SAGITTARIUS DWARF GALAXY AS A POSSIBLE PERTURBER

The impact that the Sagittarius dwarf galaxy may have had on the Galactic disc has been previously considered by several authors. Recently, using high-resolution $N$-body simulations, P11 showed that its gravitational interaction may play a significant role on shaping the morphology of the Galactic disc by inducing the formation of rings, influencing the Galactic bar and flaring the outer disc. Its interaction could also explain the formation of the Monoceros rings (Newberg et al. 2002; Quillen et al. 2009; Michel-Dansac et al. 2011; P11). However, until now, its influence on the phase-space distribution of disc stars located within the neighbourhood of the Sun has not been explored. In this section we analyse the simulations presented by P11 to characterize the effect of Sagittarius within this volume.

### 6.1 The simulations

Two simulations with different models for the Sagittarius dwarf galaxy progenitor were performed. In both cases, the primary galaxy includes an NFW DM halo, an exponential stellar disc and a central bulge following a Sérsic profile. The Light Sgr and Heavy Sgr progenitors were self-consistently initialized with a NFW DM halo and a separate stellar component following a King profile (King 1966). Table 2 summarizes the numerical values of the parameters used for these models. Following previous work on the Sgr interaction (Keselman, Nusser & Peebles 2009), the satellites were launched at 80 kpc from the galactic centre in the plane of the Milky Way, traveling vertically at 80 km s$^{-1}$ towards the North Galactic Pole. The simulations reach a present-day configuration after approximately 2.7 and 2.1 Gyr of evolution, respectively. Mass loss that would have occurred between virial radius infall and this ‘initial’ location is accounted for by truncating the progenitor DM halo mass profile at the instantaneous Jacobi tidal radius, $r_t = 23.2$ and 30.6 kpc, respectively. This leaves a total bound mass that is a factor of 3 smaller than their effective virial mass originally assigned. Each of the model Sgr progenitors experiences two disc crossings, approaching a third at the present day. The satellite first crosses the disc at a galactocentric distance of $\sim 20$ kpc approximately $\sim 1.75 \text{ Gyr}$ ago, producing the most significant perturbation. The progenitor

**Table 2.** Initial properties of the two $N$-body simulations analysed in Section 6.

| Host | | |
|------|---|---|
| DM halo | | $N_{\text{part}} = 2.65 \times 10^7$ | |
| Virial mass | $1 \times 10^{12}$ | (M$_\odot$) | |
| Scale radius | 14.4 | (kpc) | |
| Stellar disc | | $N_{\text{part}} = 3 \times 10^6$ | |
| Mass | $3.59 \times 10^{10}$ | (M$_\odot$) | |
| Scale length | 2.84 | (kpc) | |
| Scale height | 0.43 | (kpc) | |
| Stellar bulge | | $N_{\text{part}} = 5 \times 10^5$ | |
| Mass | $9.52 \times 10^9$ | (M$_\odot$) | |
| Effective radius | 0.56 | (kpc) | |
| Sérsic index | 1.28 | | |

| Satellites | | |
| Light Sgr | Heavy Sgr | $N_{\text{part}} = 1.8 \times 10^6$ |
| Virial mass | $0.32 \times 10^{11}$ | $1 \times 10^{11}$ |
| Scale radius | 4.9 | 6.5 |
| Stellar spheroid | | $N_{\text{part}} = 5 \times 10^4$ |
| Core radius | 1.5 | 1.5 |
| Tidal radius | 4 | 4 |
| Central vel. disp. | 23 | 30 | km s$^{-1}$ |

3 Note that both mechanisms could be acting simultaneously.
loses roughly 75 per cent of its DM mass (but little stellar material) during this time. In the bottom panel of Fig. 7 we show the time evolution of the satellites’ galactocentric distance. The initial disc in both Sgr-infall models is completely smooth at $t = 0$ Gyr, and only develops a mild bar when it is evolved in isolation for a few Gyr. When compared to the isolated run, the Light Sgr model results in a stronger bar (see P11). Conversely, as a result of enhanced central disc heating, the more massive satellite suppresses bar formation. The end state bar orientation, $\phi_{\text{bar}}^{\text{ini}} = 15' - 20'$, is in both cases consistent with estimates of the long bar’s orientation observed in the centre of the Milky Way, $\phi_{\text{bar}}^{\text{MW}} = 15' - 30'$ (Bissantz & Gerhard 2002). The simulations used the parallel $N$-body tree code CHANGA.

### 6.2 The phase-space distribution of solar neighbourhood like volumes

We now characterize the phase-space distribution of particles within solar neighbourhood like volumes of 1-kpc radii. In these simulations, according to the location of the Sagittarius remnant and its tidal debris, the Sun should be located at approximately $(0, -8, 0)$ kpc from the galactic centre. In order to examine the dependences of the particle’s phase-space distribution with azimuthal angle, and uncertainties on the location of the ‘Sun’ associated with the model, we have placed five spheres at different azimuthal angles, covering a total of $\approx 58'$ around the ‘Sun’. The top panel of Fig. 7 shows contour plots of the final distribution of particles in the $X-Y$ plane obtained from the Heavy Sgr simulation. The white dots trace the regions where Sgr crosses the plane of the disc and its current projection on the $X-Y$ plane. The locations of our solar neighbourhood spheres are indicated with solar symbols. As shown by P11, the gravitational interaction between the Sagittarius-like satellite and the galactic disc is sufficiently strong to induce the formation of transient spiral arms or rings. These arms can be clearly observed outside a radius of 15 kpc, but not so clearly at the solar radius. In the top panels of Fig. 8 we show the KHS of $E$ obtained from the distribution of particles located within these volumes. Let us recall that throughout this work we have kept fixed both the value of $\Delta E$ and the value of the bandwidth of the Gaussian kernel, $\sigma$. The black solid lines show the results obtained when the particle energies are computed using the analytic potential introduced in Section 4, whereas for the red dashed lines energies were computed directly from the $N$-body potential. The very good agreement between the two KHS reflects the weak dependence of the amount and distribution of features with the particular choice of the galactic potential. Note that, for comparison, the red dashed lines have been slightly shifted in energy, so that both KHS overlap in the same energy range. On average, the number of particles contained in each sphere is $\approx 10000$. It is interesting to observe that all the analysed volumes exhibit peaks in their KHS; these are features associated with density waves. We see strong dependence of the distribution and amount of peaks with azimuthal angle, $\theta$: as $\theta$ is decreased, power from the highest amplitude peak ($E \approx -1.01 \times 10^5$ km$^2$ s$^{-2}$ at $\theta \approx 29'$), or density wave, is transferred towards a secondary peak at higher energy ($E \approx -0.96 \times 10^5$ km$^2$ s$^{-2}$ at $\theta \approx 29'$). In addition, the location of each peak is shifted towards lower values of $E$, indicating that, on average, these peaks are populated by more inner particles. This is the expected behaviour from a spiral pattern travelling in this angular direction (see also section 4.2 of G12). Note the similarities between the KHS in the second top panel of Fig. 8 ($\theta \approx 18'$) with the KHS obtained from our F/G dwarf thick-disc subsample, shown in Figs 2 and 5. This result clearly indicates that some of the features observed in the KH of the Milky Way thick disc, especially the peak at $E \approx -0.97 \times 10^5$ km$^2$ s$^{-2}$, could be associated with density waves excited by the Sagittarius dwarf galaxy. An important implication of the strong azimuthal dependence observed in our simulations is that the orbital properties of the Sagittarius dwarf galaxy could be further constrained by fitting

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$^4$ The force softening length is set to roughly 0.1 of the mean disc interparticle spacing.
Figure 8. Top panels: KHs of energies obtained from the Heavy Sgr simulation. Each panel shows the KH obtained from the distribution of particles within a solar neighbourhood like sphere located at a different galactocentric azimuthal angle, $\theta$. The black solid lines show KHs obtained after computing particle’s energy using the analytic potential described in Section 4. The red dashed lines show the KHs obtained after computing particle’s energies from the N-body potential. The shaded regions indicate errors associated with poor sampling of the underlying distribution (see Section 4.1). The angle $\theta$ is measured clockwise, starting from the negative Y axis in Fig. 7. The azimuthal locations of the spheres are indicated in the top-left corner of each panel. Note that all the KHs exhibit multiple peaks associated with density waves crossing the solar neighbourhood like volumes. Furthermore, the locations of these peaks strongly depend on the azimuthal location of the sphere. Note also the good agreement between the second panel ($\theta \approx 18^\circ$) and the KHs obtained for our F/G dwarf thick-disc subsample shown in Figs 2 and 5. Middle panels: same as the top panels, but for the Light Sgr simulation. Note that, as expected for a less massive satellite, the peaks previously observed in the KHs of the Heavy Sgr model are either very mild or not present at all. Bottom panels: same as the top panels, but now for spheres located at a different galactocentric radius, $R$. The spheres are located at an azimuthal angle $\theta = 0^\circ$. The galactocentric distance of the spheres are indicated in the top-left corner of each panel. The black solid and blue dashed lines show the KHs obtained from the Heavy Sgr and Light Sgr simulations, respectively. For the Heavy Sgr simulation, the locations and amplitude of the peaks in the KHs strongly depend on the radial position of the spheres. Note also the similarities between the second panel ($R = 7.5$ kpc) and the KHs obtained for our F/G dwarf thick-disc subsample. For the Light Sgr simulation, mild signatures of density waves can be observed only in the outer spheres, where the perturbation from the satellite galaxy is stronger.

The locations and amplitude of the significant peaks in the models to those observed in stellar samples.

In the middle panels of Fig. 8 we show the results of the previous analysis obtained from the Light Sgr model. The solar neighbourhood like spheres were placed at the same locations. As before, the black solid lines show the KHs obtained after computing particle energies using the analytic potential, whereas for the red dashed lines the N-body potential was used. As expected from a less massive satellite (and thus a weaker perturber), the peaks previously observed in the KHs of the Heavy Sgr model are either very mild or not present at all. It is interesting to note that, as previously discussed, the Light Sgr model results in a much stronger bar than the Heavy Sgr model. The more massive satellite suppresses bar formation as a result of enhanced central disc heating. This clearly demonstrates that none of the observed features in these simulations could be associated with resonances with the galactic bar. Otherwise, we would expect to observe higher amplitude features in the Light Sgr model’s KHs as a result of the interaction with the stronger bar. Thus, models of the Sagittarius dwarf galaxy progenitor with a total mass $\leq 10^{10.5}$ M$_\odot$ could be ruled out. Moreover, note that its total mass could be further constrained by comparing the amplitudes of the significant peaks observed in the KHs of models with those of the Milky Way disc.

In the bottom panels of Fig. 8 we explore solar neighbourhood like spheres of 1-kpc radius centred at different galactocentric distances. The spheres are separated by 0.5 kpc, and are all located at $\theta = 0^\circ$. The black solid lines show the KH obtained from the Heavy Sgr model. A strong dependence on the amplitude of each peak with galactocentric radius can be observed. As we move towards the galactic centre, we better sample inner density waves, represented by peaks at lower energies. Again, note the similarities between the KHs obtained in the inner spheres (e.g. $R = 7.5$ kpc) and the KHs obtained for our F/G dwarf thick-disc subsample. For the Light Sgr simulation, mild signatures of density waves can be observed only in the outer spheres, where the perturbation from the satellite galaxy is stronger.
and those obtained from our F/G dwarf sample (see e.g. Fig. 5). The blue dashed lines in the bottom panels of Fig. 8 show the KH obtained from the Light Sgr model. As expected, mild signatures of density waves can be observed only in the outer spheres, where the perturbation from the satellite galaxy is stronger. In Fig. 9 we show the time evolution of the KH of particles located within a given solar neighbourhood like sphere for \( t \approx 2.5 \) Gyr. To track this volume over time, our sphere is rotating with an angular frequency set by the velocity of the LSR, obtained after correcting the final mean rotational velocity profile for axisymmetric drift. The KHs are shown at four different times: the initial conditions, the two pericentre passages and the present-day configuration. The black solid lines show KHs obtained from the Heavy Sgr model. Note the smooth distribution of particles in energy space at \( t = 0 \). Strong perturbation in the disc particle energy distribution are only excited after the first pericentre passage of the satellite. The blue dashed lines show the KHs obtained from the Light Sgr model. Note the approximately smooth energy distribution at all times.

7 SUMMARY AND CONCLUSIONS

We have analysed the SEGUE F/G dwarf and the SCH06 stellar samples in search for imprints of minor-merger events in the Milky Way disc. In contrast to a number of previous studies, we look for perturbations in the phase space of the host disc rather than merger remnants. We apply the same analyses to high-resolution N-body simulations of the interaction between the Sagittarius dwarf galaxy and the Milky Way. We summarize our results as follows.

(i) The \( \alpha \)-enhanced, likely thick-disc F/G dwarf subsample exhibits significant peaks in the stellar energy KH. Conversely, the thin-disc subsample shows a much smoother distribution. This is consistent with the expectation that merger-induced perturbations in the host galaxy disc (e.g. the Milky Way) create structure in the thin-disc subsample, whereas they are less pronounced in the thick disc. This result is consistent with the expectation that thin-disc stellar population is less affected by mergers.

(ii) We show that, to unambiguously identify merger-induced waves (ringing), samples of stars with velocity errors \( V_{\text{err}} < 11 \) km s\(^{-1}\) are required. This depends on the time since the waves were excited, as well as on the mass of the perturber.

(iii) Complementary evidence of ringing can be obtained from the SCH06 catalogue. The energy KH of stars here also reveals peaks, most of them remarkably consistent with those observed in the F/G dwarf sample.

(iv) Simulations of the interaction between the Milky Way and the Sagittarius dwarf galaxy show that a relatively massive progenitor (i.e. masses of \( \approx 10 \) per cent of the host) can induce density waves in the Galactic disc. Furthermore, the features seen in the energy KH of the observational data can be qualitatively well reproduced with these simulations. This is interesting since, by matching the features in the KHs of both models and observations, one could attempt to further constrain the orbital properties of Sagittarius, thanks to the strong azimuthal and radial dependence of the distribution peaks. Note, however, that other possible origins for these perturbations need to be ruled out before performing this kind of analysis.

(v) On the contrary, low-mass models of Sagittarius barely excite density waves in the disc. Thus, if we assume that the observed peaks in the KH of the F/G dwarf sample are the response of the Galactic disc to the tidal interaction with Sgr, we could rule out such low-mass models. Furthermore, by matching the amplitudes of the peaks, one could attempt to further constrain the total mass of the Sagittarius progenitor.

Comparing Figs 5 and 8, we note that variations in the azimuthal and radial positions of the Sun with respect to the Sagittarius orbital plane can result in similar structure in the stellar energy distribution. This degeneracy can be broken by studying in detail the variation of features in the stellar phase-space distribution when position in the disc is varied. This in turn requires larger and deeper stellar samples, which will become available in ongoing and future surveys, such as APOGEE (Majewski et al. 2010), HERMES (Wylie-de Boer & Freeman 2010) and ultimately Gaia (Perryman et al. 2001).

Although we cannot fully discard the possibility that the observed features have some secular origin, the much smoother energy distribution of the thin-disc population makes this scenario unlikely. If these features had originated by resonant interaction with, for example, the Galactic bar, we would expect them to be stronger in the thin disc, rather than in the thick disc. This result is consistent with the hypothesis that features associated with ringing should last longer in the thick disc. Thick-disc stars spend relatively little time...
near the Galactic plane, where heating from spiral arms or the bar and scattering by giant molecular clouds is most vigorous. In addition, features generated by the bar or spiral arms can be observed as lumps in the $u-v$ plane. We have explored this plane, and found no significant overdensities that could be linked to this kind of secular perturbations.

In this study we considered simulations with two different masses for the Sagittarius progenitor, representing a lower limit ($M_{\text{vir}} = 10^{10.5} \, M_\odot$) and an upper limit ($M_{\text{vir}} = 10^{11} \, M_\odot$). We have found that the Light Sgr cannot explain the structure seen in the energy distribution of our observed samples. On the other hand, the Heavy Sgr model creates strong disturbances in the Milky Way's disc, resulting in prominent peaks in the energy $K_H$ in localized spatial volumes, perhaps even stronger than what is seen in the observations (compare Figs 5 and 8). As shown by G12, satellites with masses 10 and 20 per cent of the mass of their host generate density waves, which can be followed for no longer than, respectively, 1 and 2 Gyr after the satellite’s full disruption. Close encounters between massive substructures and galactic discs should be common occurrences in a $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology since $z = 1$ (Kazantzidis et al. 2009). However, the short relaxation time-scale involved and the lack of observational evidence of a merger with such characteristics in the last 1–2 Gyr suggest that Sgr is the most likely perturber.

It is important to note that all simulations analysed in this work considered initially stable, unperturbed stellar discs. It remains to be explored how a previously perturbed disc, either by a merger event or other dynamical process, would react to the tidal interaction with a satellite galaxy such as Sgr. Future studies should consider simulations spanning a range of masses for the Sgr progenitor, between the two limits we presented here, as well as varying Galactic disc models, which can be tuned more finely as our knowledge of the dynamics of the Milky Way expands. In addition, it remains to be studied whether perturbations from multiple satellite galaxies can be successfully disentangled.

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