Is the Milky Way ringing? The hunt for high-velocity streams

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ABSTRACT
We perform numerical simulations of a stellar galactic disc with initial conditions chosen to represent an unrelaxed population which might have been left following a merger. Stars are unevenly distributed in radial action angle, though the disc is axisymmetric. The velocity distribution in the simulated solar neighbourhood exhibits waves travelling in the direction of positive \( v \), where \( u, v \) are the radial and tangential velocity components. As the system relaxes and structure wraps in phase space, the features seen in the \( u-v \) plane move closer together. We show that these results can be obtained also by a semi-analytical method. We propose that this model could provide an explanation for the high-velocity streams seen in the solar neighbourhood at approximate \( v \) in km s\(^{-1}\), of \(-60 (HR 1614), -80, -100 (Arcturus) \) and \(-160 \). In addition, we predict four new features at \( v \approx -140, -120, 40 \) and \( 60 \) km s\(^{-1}\). By matching the number and positions of the observed streams, we estimate that the Milky Way disc was strongly perturbed \( \sim 1.9 \) Gyr ago. This event could have been associated with Galactic bar formation.

Key words: stellar dynamics – Galaxy: evolution – Galaxy: kinematics and dynamicsn – solar neighbourhood – galaxies: evolution.

1 INTRODUCTION
The formation and evolution of galaxies is one of the most important topics in contemporary astrophysics. High-redshift cosmology provides insight into the evolution of global galaxy properties, but is unable to probe the internal kinematics and chemistry on sub-galactic scales. The Milky Way (MW), on the other hand, contains a vast amount of fossil evidence encoded in the motions and chemical properties of its stars. The Galaxy is the only galaxy within which we can obtain information at the level of detail required to distinguish robustly between different formation scenarios. Unfortunately, however, the precise structure of the MW remains a topic of debate. In order to make progress in this field we need to differentiate between different Galactic models.

As part of this effort, models aimed at explaining asymmetries in the solar neighbourhood (SN) velocity space as the result of internal (spiral and/or bar structure) or external (satellite mergers) agents have been explored in the past several decades. Hipparcos data revealed a non-smooth local velocity distribution of stars (Chereul, Creze & Bienayme 1998; Dehnen 1998; Chereul, Crézé & Bienaymé 1999). These stellar streams cannot simply be dissolved clusters (Famaey et al. 2007), but could be caused by dynamical effects within the MW disc or satellite mergers. Some of these features have been used as tracers of non-axisymmetric Galactic disc structure and employed in estimating parameters of the MW central bar (Dehnen 2000; Fux 2001; Chakrabarty 2007; Minchev, Nordhaus & Quillen 2007) and spirals (Lépine et al. 2001; Quillen & Minchev 2005; Chakrabarty 2007). However, dynamical instabilities in the Galactic disc have been found to only relate to velocities in the range \( u, v \sim \pm 50 \) km s\(^{-1}\), where \( u \) and \( v \) are the radial and tangential galactocentric velocities of SN stars, respectively. At this time there is no evidence that spiral or bar structure can cause high-velocity streams, thus, these are usually attributed to merger events. For instance, the Arcturus stream at \( v = -100 \) km s\(^{-1}\) has been interpreted as originating from the debris of a disrupted satellite (Navarro, Helmi & Freeman 2004; Helmi et al. 2006). Two recently discovered streams at \( v \sim 80 \) km s\(^{-1}\) (Arifyanto & Fuchs 2006) and \( v \sim -160 \) km s\(^{-1}\) (Klement, Fuchs & Rix 2008) were assigned similar origin, based on their kinematics. There is plenty of evidence for past and ongoing accretion of small objects by the MW, the most dramatic one being the highly disrupted Sgr dwarf galaxy identified by Ibata, Gilmore & Irwin (1994, 1995). But what about clues of more massive MW mergers?

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Cosmological simulations show that massive minor mergers are likely to have happened during the lifetime of a MW-sized host system. Early generations of numerical simulations (Quinn, Hernquist & Fullagar 1993; Walker, Mihos & Hernquist 1996) have investigated the heating of galactic discs by mergers, finding that discs heated in this way are similar to the MW thick disc. By considering realistic satellite orbits and conditions, more recent attempts to model disc heating in a cosmological context suggest smaller efficiency than previously thought. For instance, Hopkins et al. (2008) estimated that the MW could have survived as many as ~5–10 minor (mass ratio ~1:10) mergers in the last 10 Gyr. By estimating the maximum mass ratio merger for a MW-sized galaxy, the authors point out that the Galaxy could even have survived mergers of mass ratio ~1:4–1:3 without destroying the disc. Kazantzidis et al. (2008) estimated the number of massive subhaloes accreted since \( z \sim 1 \) to be at least one object with a mass \( \sim M_{\text{disc}} \) and five objects more massive than 20 per cent \( M_{\text{disc}} \). These findings are consistent with simulations by other groups (Benson et al. 2004; Stoehr 2006; De Lucia & Helmi 2008; Stewart et al. 2008; Villalobos & Helmi 2008; Purcell, Kazantzidis & Bullock 2009). Even though massive minor mergers may be less frequent, they are able to reach the centre of the host system (provided they are also dense) thanks to dynamical friction, causing important changes in the structure and kinematics of the host disc. By using data from the Two Micron All-Sky Survey (2MASS), Cole & Weinberg (2002) estimated that the MW bar is likely to have formed more recently than 3 Gyr ago and suggested that this event could have been triggered by a now-merged satellite. Formation of central bars as the result of satellite–disc encounters has also been observed in N-body simulations (Walker et al. 1996; Kazantzidis et al. 2008).

All this evidence from both observations and simulations implies that merging satellites could contribute to the heating of the MW disc. Is it possible to relate the effects of such an event to features in the local velocity space (\( u−v \) plane)? Instead of interpreting streams as debris from disrupted small satellites, as done by Navarro et al. (2004), Arifyanto & Fuchs (2006), Helmi et al. (2006) and Klement et al. (2008), we ask a different question here: Is it possible that some overdensities in the SN velocity space are simply the response of the MW disc to the sudden energy kick imposed by a massive satellite in the past?

The signature of this perturbation will be present in the MW stellar kinematics during the relaxation time after the event. Depending on the time of this event, it is possible that the Galactic disc is still undergoing relaxation, although at this time the impact imprint may be extremely faint. However, because stars of the thick disc spend relatively little time near the galactic plane, where the spiral arm heating and scattering by giant molecular clouds is most vigorous, radial mixing within the thick disc is unlikely to wipe out the signature of a past event too quickly.

In this Letter we look at the evolution of a non-relaxed galactic disc and its manifestation in the velocity distribution of a simulated SN.

2 SIMULATIONS OF AN UNRELAXED DISC

At present it is not computationally feasible to achieve the statistics needed for resolving a small spatial region with N-body simulations, even in the case of a single galaxy. Thus, a realistic galaxy collision simulation does not provide the resolution needed for our purposes, i.e. resolve a fictitious SN to look for structure in the local velocity space. We choose initial velocities for particles axisymmetrically by means of Gaussian distributions in \( u \) and \( v \) with corresponding standard deviations \( \sigma_u \) and \( \sigma_v \), consistent with a hot stellar population. However, we purposely choose them so that they are not evenly distributed in their radial oscillation. This serves as a proxy for choosing a population that is unrelaxed or unevenly distributed in phase space, such as might be left after a merger. We further simplify the problem by considering only two dimensions, assuming the vertical motion of stars is decoupled from the motion in the plane of the Galaxy. We are mainly concerned with a flat rotation curve but also discuss the effect of a decreasing and increasing one in Section 4. In addition to an axisymmetric system we also simulate a disc perturbed by a central bar as a pure quadrupole. A detailed description of the perturbation can be found in Minchev et al. (2007). To explore the time development of the system, we do not time average over position and velocity vectors, as it is frequently done in test-particle simulations (Dehnen 2000; Fux 2001; Minchev & Quillen 2007) where no dynamical development of the system is expected. To convert to real units we use local standard of rest (LSR) tangential velocity of 220 km s\(^{-1}\), and galactocentric distance of 7.8 kpc.

Note that the Gaussian distributions in \( u \) and \( v \) provide initial conditions (ICs) sampled non-uniformly in \( \theta \), the radial epicyclic angle. These ICs were found to induce an initial radial expansion in the disc consistent with the \( N \)-body simulations by Quinn et al. (1993) and Walker et al. (1996), where they found that the host discs respond by spreading both radially and vertically. However, after a couple of rotations the density distribution appears smooth and is axisymmetric.

3 RESULTS

3.1 Density waves in velocity space

We now look for the effect of our ICs on a simulated SN velocity distribution. In Fig. 1 we show the time development of the local velocity field in three different ways. The first row shows the \( u−v \) plane (contours) and the \( v \) distribution (solid line). The second row plots \( (u^2 + 2v^2)^{1/2} \) versus \( v \) as done by Arifyanto & Fuchs (2006) and Klement et al. (2008). In this simulation \( \sigma_u = 50 \) km s\(^{-1}\). The sample shown is limited to a radius of 100 pc around our fictitious Sun. We show six time outputs up to \( t = 10 \) rotations at \( r_o \). Note that features in the \( u−v \) plane get closer together as time increases. We interpret this as wrapping in phase space on a time-scale associated with the epicyclic frequency. The features are not oriented along constant eccentricity surfaces as predicted by Helmi et al. (2006) for particles trapped from a minor-merging galaxy. In our case the axes are oriented in the opposite direction, since they are centred on \((u, v_0) = \) 0, in other words these are constant energy surfaces.

Note that the features in the \( u−v \) plane are manifested in the tail of the \( v \) distribution, as well as in \( (u^2 + 2v^2)^{1/2} \), as overdensities travelling in the direction of positive \( v \). In Section 3.3 these are used to match to high-velocity streams observed in the SN stellar population.

It is important to make a point here concerning the average distance of our sample from the Sun. Because of the differential rotation of the Galaxy, at radii interior to \( r_o \), the relaxation is completed faster, whereas the opposite is true for stellar samples at \( r > r_o \). Thus, for a given time, the separation of features in the \( u−v \) plane depends on the galactocentric distance of our sample. Consequently, as sample depth increases we sample a large range of Galactic radii causing the waves to interfere and either enhance or (mostly) wipe out structure in the \( u−v \) plane.
To better understand the mechanism giving rise to these ripples in velocity space, next we use the epicyclic approximation to reproduce the numerical results just described.

### 3.2 Semi-analytical approach

We assume a flat rotation curve with the parameter \( \gamma \equiv 2 \Omega / \kappa = \sqrt{2} \), where \( \Omega \) and \( \kappa \) are the angular rotation rate and epicyclic frequency of a particle in a circular orbit. Since we work in units of \( v_0 \) and \( r_0 \), the gravitational potential for a flat rotation curve \( \Phi(r) = v_0^2 \ln (r/r_0) \) is zero for stars in the SN. For every position on the \( u-v \) plane energy and angular momentum can be computed as \( E(u, v) = (1/2) [u^2 + (1 + v)^2] \) and \( L(v) = 1 + v \).

Dehnen (1999) derived a good approximation for the frequency of epicycles accurate at large epicyclic amplitude (his equation 30d):

\[
\omega_R(L, E) \approx \frac{\kappa(E)}{[1 + (1/4)e^2(\gamma - 1)(\gamma - 2)]},
\]

where \( e^2 = 1 - L^2/L^2(E) \) (2)

is the square of the orbital eccentricity (his equation 30b). These functions depend on \( \kappa(E) \) and \( L(E) \), which are the epicyclic frequency and the angular momentum for a circular orbit with energy \( E \):

\[
\kappa(E) = \sqrt{2} \exp \left( \frac{1}{2} - E \right),
\]

\( L(E) = \exp \left( E - \frac{1}{2} \right) \).

where we have used expressions from table 1 by Dehnen (1999), given in units of the circular velocity. Since \( \omega_R \) depends on \( L \) and \( E \), it can be computed for every position on the \( u-v \) plane in the SN.

We assume that our initial particle distribution is not evenly distributed in the angle associated with epicyclic motion, \( \theta \). If the initial phase-space density distribution is skewed along this angle at \( \theta_0 \), then at a time \( \Delta t \) later there will be a maximum of particles at \( \theta(L, E) = \theta_0 + \omega_R(L, E)\Delta t \).

To mimic the effect of this we construct a weighting function that gives a maximum at \( \theta(L, E) = 0 \mod 2\pi \):

\[
w(L, E) = \exp(-e/e_0) [1 + e^2 \cos(\omega_R t)] \]

(6)

where the exponential function mimics a Gaussian velocity dispersion and \( e_0 \) is a constant. In the above equation \( \omega_R \) and \( e \) depend on \( L \) and \( E \). Equation (7) can be computed for every position on the \( u-v \) plane for different values of \( t \). The result is shown in Fig. 2 and looks remarkably close to what is seen in the test-particle simulations.

![Figure 2. The \( u-v \) plane computed using a weighting function utilizing equation (30b) from Dehnen (1999). Note the striking similarity to our numerical simulations (Fig. 1).](image-url)
Figure 3. Three ways of plotting the same data, as done in Fig. 1, for a particular time matching four observed high-velocity local streams (dashed lines). From left to right, in km s$^{-1}$, these are STR1 at $v \approx -160$, Arcturus at $v \approx -100$, STR2 at $v \approx -80$ and HR 1614 at $v \approx -60$. The dotted lines at $v \approx -140$, $-120$, $40$ and $60$ km s$^{-1}$ show the positions of four new streams this new model predicts. Note that the density oscillations giving rise to these features have an amplitude of less than 1 per cent.

3.3 Relating to moving groups

We now discuss the possibility that ringing in the Galaxy is the reason for four high-velocity streams observed in the local velocity field. We search for a particular time in our synthetic velocity distributions, for which we get a satisfactory match to all four. Fig. 3 presents velocity field plots from our numerical simulations for time $t = 8.67$ rotations at $r_0$, in three different ways as in Fig. 1. The dashed lines indicate the position of the observed overdensities. From left to right are these as follows: (1) a high-velocity stream at $v = -160 \pm 20$ km s$^{-1}$ (hereafter STR1) was recently reported by Klement et al. (2008) which, based on its kinematics, is thought to belong to the thick disc. (2) Arcturus is a moving group lagging the LSR by 100 km s$^{-1}$. Its metal-poor nature and significant age are consistent with the thick disc. A detailed investigation of its origin by Williams et al. (2009) found that the chemical results are consistent with a dynamical origin but do not entirely rule out a merger one. The upper left-hand panel in Fig. 1 by Williams et al. (2009) presents a $u-v$ plot of the Arcturus stream. Centred on a narrow $v$, it spreads over the range $-100 < u < 100$, consistent with our results (left-hand panel in Fig. 3). (3) A stream with characteristics appropriate for the thick disc at $v = -80$ km s$^{-1}$ (hereafter STR2) was found by Arifyanto & Fuchs (2006) using data extracted from various catalogues. (4) The moving group HR 1614 at $v = -60$ km s$^{-1}$ is thought to be a dispersed open cluster because of its chemical homogeneity (Eggen 1992; De Silva et al. 2007) at a distance of 40 pc from the Sun. It is intriguing that, similarly to Arcturus, in the $u-v$ plane this stream has a spread in $u$, again consistent with Fig. 3. However, $-50 < u < 20$ km s$^{-1}$ (fig. 5 in De Silva et al. 2007), i.e. the corresponding wave giving rise to HR 1614 is distorted toward negative $u$. This is consistent with the effect of the bar, given the proximity of this overdensity to the Hercules stream. Note that our interpretation for HR 1614’s location at $v = 60$ km s$^{-1}$ does not contradict the possibility of it being a dispersed cluster, as long as it is older than the time of the merger event, since the streams in the model proposed here are only defined by their kinematics.

In addition to the four observed streams, our new model predicts overdensities at approximately every 20 km s$^{-1}$. However, in the range $-50 < v < 50$ km s$^{-1}$, the central peak of the velocity distribution dominates. Thus, we are left with four new, easily identifiable overdensities at $v \approx -140$, $-120$, $40$ and $60$ km s$^{-1}$, indicated by the dotted lines in Fig. 3.

Figure 4. Observational data form Nordström et al. (2004) and Schuster et al. (2006) combined samples. We select stars in the metallicity range $-1.1 < [\text{Fe/H}] < -0.55$ dex. The dashed and dotted lines indicate the observed and predicted overdensities as in Fig. 3.

In order to look for the streams our model predicts, we combined the observational samples by Nordström et al. (2004) and Schuster et al. (2006). We select a thick disc dominated sample by considering the metallicity range $-1.1 < [\text{Fe/H}] < -0.55$ dex. In Fig 4 we present the result for sample depths $d_{\text{max}} = 80$ and 150 pc in the same fashion as the left-hand panel of Fig. 3. With this small number of stars ($N = 451$ and 766 for $d_{\text{max}} = 80$ and 150 pc), this result is not statistically significant to provide convincing evidence for the validity of our model. However, the resemblance of the observed $v$ distribution to the ones resulting from our simulations and semi-analytical approach is striking.

4 DISCUSSION AND CONCLUSIONS

We have shown that an axisymmetric galactic disc subjected to an initial energy kick approximating a massive Galactic merger induces waves in the SN velocity field propagating in the direction of positive $v$, which appear as overdensities in the tail of the tangential velocity distribution. By comparing our synthetic models to observations, a satisfactory match to four SN high-velocity streams is achieved toward the end of the disc relaxation at $t = 8.67$ SN rotations (Fig. 3). In addition, we predict the existence of four (or more) new features at $v \approx -140$, $-120$, $40$ and $60$ km s$^{-1}$. Our results allow us to make an estimate for the time of the event. For a galactocentric distance of 7.8 kpc and a LSR tangential velocity of 220 km s$^{-1}$, $t = 8.67$ rotations corresponds to $\approx 1.9$ Gyr. If our model is correct, then all observed and predicted streams must be older than the time of the disc-stirring event. All four of the known features discussed in Section 3.3 have ages $> \sim 2$ Gyr, which is consistent with our prediction for the time of the impact. This model also argues against purely diffusive stochastic heating models (Jenkins & Binney 1990; Sellwood & Binney 2002; Minchev & Quillen 2006) for the Galactic disc.

In addition to a flat rotation curve, we have also considered a power-law initial tangential velocity $v_{\phi} = v_{\phi}(r/r_0)^{\beta}$ with $\beta = 0.2, -0.2$ corresponding to a rising and a declining rotation curve, respectively. We found that the separation of the features in the $u-v$ plane decreases with time more rapidly for $\beta = 0.2$ and more slowly in the case of $\beta = 0.2$, as expected. However, at $r_0$ our results remained the same. The $\sim 20$ km s$^{-1}$ separation of features in the local velocity field arises naturally as a result of the galactocentric distance and tangential velocity of the LSR, i.e. it is determined only by the LSR angular velocity. Thus, not only this model is independent of the MW rotation curve, but also it can be used to provide constraints on $\beta$ by observations of the velocity field at Galactic radii different than $r_0$. 

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Features in the $u-v$ plane represent curves of constant energy and are oriented opposite to the constant eccentricity curves in Helmi et al. (2006)'s model. As more SN stars are surveyed with RAVE (Radial Velocity Experiment) and GAIA, the shape of these will be better resolved and we will be able to tell the difference between Helmi's model and ours. We predict a shift in location of features as a function of galactocentric radius (closer together for shorter radii) as the distance between the features depends on the epicyclic frequency. Deeper surveys, such as ARGOS, SEGUE, BRAVA and APOGEE, could search for this shift in the way suggested by Minchev & Quillen (2008).

We have checked that the growth, or longer term effect, of a central bar does not cause similar features in the $u-v$ plane, thus the bar is not responsible for such radial perturbations. However, an increase in central mass associated with a merger could cause such variations in the epicyclic action-angle distribution. From recent cosmological simulations it is now known that satellites of mass variations in the epicyclic action-angle distribution. From recent cosmological simulations it is now known that satellites of mass ratio to host disc $\geq 1:10$ merge on highly eccentric, nearly radial orbits in a couple of dynamical times (Hopkins et al. 2008). Then they quickly merge by dumping their mass in the centre of the host disc. It would appear to be simple to look for initial conditions from an $N$-body simulation. However, this is actually non-trivial for a number of reasons: (1) not enough particles to resolve high-velocity structure; (2) large range of possibilities; (3) time-dependent phenomena associated with mergers.

Our short time-scale is consistent with the estimated age of the Galactic bar, as measured by Cole & Weinberg (2002) ($<3$ Gyr ago). This suggests that the same event that caused the formation of the Galactic bar could have left the stellar disc unrelaxed, thus giving rise to the observed high-velocity streams. Another possibility for stirring up the MW disc is the $oCen$ event (Bekki & Freeman 2003; Meza et al. 2005).

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