IS THE MILKY WAY RINGING? THE HUNT FOR HIGH VELOCITY STREAMS

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Abstract

We perform numerical simulations of a stellar galactic disk 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 disk is axisymmetric. The velocity distribution in the simulated Solar neighborhood exhibits waves traveling 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 \(uv\)-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 neighborhood at approximate \(v\) in km/s, of -60 (HR 1614), -80 (Arifyanto and Fuchs 2006), -100 (Arcturus), and -160 (Klement et al. 2008). In addition, we predict four new features at \(v \approx -140, -120, 40\) and 60 km/s. By matching the number and positions of the observed streams, we estimate that the Milky Way disk was strongly perturbed \(\sim 1.9\) Gyr ago. This event could have been associated with Galactic bar formation.

Subject headings: stellar dynamics

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 Neighborhood (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 (Dehnen 1998, Chereul et al. 1998, 1999). These stellar streams cannot simply be dissolved clusters (Famaey et al. 2007), but could be caused by dynamical effects within the MW disk or satellite mergers. Some of these features have been used as tracers of non-axisymmetric Galactic disk structure and employed in estimating parameters of the MW central bar (Dehnen 2000, Fuchs 2001, Minchev et al. 2007, Chakrabarty 2007) and spirals (Lépine et al. 2001, Quillen and Minchev 2007, Chakrabarty 2007). However, dynamical instabilities in the Galactic disk have been found to only relate to velocities in the range \(u, v \sim \pm 50\) km/s, where \(u, v\) are the radial and tangential galactocentric velocities of SN stars, respectively. At this time there is no evidence that spiral or bar structures can cause high velocity streams, thus, these are usually attributed to merger events. For instance, the Arcturus stream at \(v = -100\) km/s, has been interpreted as originating from the debris of a disrupted satellite (Navarro et al. 2004, Helmi et al. 2006). Two recently discovered streams at \(v \sim 80\) km/s (Arifyanto and Fuchs 2006) and \(v \sim -160\) km/s (Klement et al. 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 et al. 1994, 1995. But what about clues of more massive MW mergers?

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 et al. 1993, Walker et al. 1996) have investigated the heating of galactic disks by mergers, finding that disks heated in this way are similar to the MW thick disk. By considering realistic satellite orbits and conditions, more recent attempts to model disk heating in a cosmological context suggest smaller efficiency than previously thought. For instance, Hopkins et al. (2008) estimated that the Milky Way could have survived as many as \(\sim 5-10\) minor (mass ratio to host disk \(\sim 1:10\)) 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 \(\sim 1 : 4 - 1 : 3\) without destroying the disk. 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 \(20\% M_{\text{disc}}\). These findings are consistent with simulations by other groups (Benson et al. 2004, Stoehr 2008, De Lucia and Helmi 2008, Villalobos and Helmi 2008).
Stewart et al. [2008] and Purcell et al. [2009]. Even though massive minor mergers may be less frequent, they are able to reach the center 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 and Weinberg [2002] estimated that the Milky Way 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-disk 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 (uv-plane)? Instead of interpreting streams as debris from disrupted small satellites, as done by Navarro et al. (2004); Helmi et al. (2004); Arifyanto and Fuchs (2006; 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 disk 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 disk is still undergoing relaxation, although at this time the impact imprint may be extremely faint. However, because stars of the thick disk 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 disk 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 disk and its manifestation in the velocity distribution of a simulated SN.

2. SIMULATIONS OF AN UNRELAXED DISK

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 3. In addition to an axisymmetric system we also simulate a disk 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 and 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, 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 disks 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 figure 1 we show the time development of the local velocity field in three different ways. The first row shows the uv-plane (contours) and the $v$ distribution (solid line). The second row plots $(u^2+2v^2)^{1/2}$ versus $v$ as done by Arifyanto and Fuchs (2006) and Klement et al. (2008). In this simulation $\sigma_u = 50 \text{ km/s}$. The sample shown is limited to a radius of 100 pcs around our fictitious Sun. We show six time outputs up to $t = 10$ rotations at $r_0$. Note that features in the uv-plane get closer together as time increases. We interpret this as wrapping in phase space on a timescale 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 arcs are oriented in the opposite direction, since they are centered on $(u, v - v_0) = 0$, in other words these are constant energy surfaces.

Note that the features in the uv-plane are manifested in the tail of the $v$-distribution, as well as in $(u^2+2v^2)^{1/2}$, as overdensities traveling 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 $r_0$ the relaxation is completed faster, whereas the opposite is true for stellar samples at $r > r_0$. Thus, for a given time, the separation of features in the uv-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 uv-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
Figure 1.— Time development of the local velocity field for an axisymmetric disk with ICs as described in the text, presented in three different ways. First row shows the $uv$-plane (contours) and the tangential velocity distribution (solid line). The second row plots $(u^2 + 2v^2)^{1/2}$ versus $v$. The sample shown is limited to a radius of 100 pc from our fictitious Sun. We show six time outputs up to $t = 10$ SN rotations. As time increases features get closer together as phase wrapping takes place.

Figure 2.— The $uv$-plane computed using a weighting function utilizing eq. 30b from Dehnen (1999). Note the striking similarity to our numerical simulations (figure 1).

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 $\theta(L, E) = 0 \mod 2\pi$.

$$w(L, E) = \exp\left(-\epsilon/e_0\right)(1 + \epsilon^2 \cos(\omega_R t))$$

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

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. Figure 3 presents velocity field plots from our numerical simulations for time $t = 8.67$ rotations at $r_0$, in three different ways as in figure 1. The dashed lines indicate the position of the observed overdensities. From left to right these are as follows: (1) A high velocity stream at $v = -160 \pm 20$ km/s (hereafter STR1) was recently reported by Klement et al. (2008) which, based on its kinematics, is thought to belong to the thick disk. (2) Arcturus is a moving group lagging the LSR by 100 km/s. Its metal-poor nature and significant age are consistent with the thick disk. A detailed investigation of its origin by Williams et al. (2008) 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 figure 1 by Williams et al. (2008) presents a $uv$-plot of the Arcturus stream. Centered on a narrow $v$, it spreads over the range $-100 < u < 100$, consistent with our results (left panel in figure 3). (3) A stream with characteristics appropriate for the thick disk at $v = -80$ km/s (hereafter STR2) was found by Arifyanto and Fuchs (2006) using data extracted from various catalogues. (4) The moving group HR 1614 at $v = -60$ km/s, 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 $uv$-plane this stream has a spread in $u$, again consistent with figure 3. However, $-50 < u < 20$ km/s (figure 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 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. However, in the range $-50 < v < 50$ km/s, 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, indicated by the dotted lines in figure 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 disk component dominated by the metallicity range $-1.1 < [\text{Fe/H}] < -0.55$ dex. In figure 4 we present the result for sample depths $d_{\text{max}} = 80$ and $d_{\text{max}} = 150$ pc in the same fashion as the left-hand panel of figure 3. With this small number of stars (N=451,766 for $d_{\text{max}} = 80, 150$ 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 disk 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 disk relaxation at $t = 8.67$ SN rotations (figure 3). In addition, we predict the existence of four (or more) new features at $v \approx -140, -120, 40$ and 60 km/s. Our results allow us to make an estimate for the time of the event. For a Galacticentric distance of 7.8 kpc and a LSR tangential velocity of 220 km/s, $t = 8.67$ rotations corresponds to $\sim 1.9$ Gyr. If our model is correct, then all observed and predicted streams must be older than the time of the disk 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 and Binney 1990; Sellwood and Binney 2002; Minchev and Quilis 2006) for the Galactic disk.

In addition to a flat rotation curve, we have also considered a power law initial tangential velocity $v_\theta = v_0 (r/r_0)^\beta$ 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 $uv$-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 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 is this model independent of the MW rotation curve, but it can be used to provide constraints on $\beta$ by observations of the velocity field at Galactic radii different than $r_0$.

Features in the $uv$-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 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 and Quillen (2008).

We have checked that the growth, or longer term effect, of a central bar does not cause similar features in the $uv$-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 ratio to host disk $\geq 1 : 10$ 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 center of the host disk. It would appear to be simple to look for initial conditions from an N-body simulation. However this is actually nontrivial 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 timescale is consistent with the estimated age of the Galactic bar, as measured by Cole and Weinberg (2002) (< 3 Gyr ago). This suggests that the same event that caused the formation of the Galactic bar could have left the stellar disk unrelaxed, thus giving rise to the observed high velocity streams. Another possibility for stirring up the MW disk is the $\omega$Cen event (Bekki and Freeman 2003; Meza et al. 2005).

Our choice of ICs for an unrelaxed disk is arbitrary. N-body simulations could be explored to see if such a distribution could arise from a merger and motivate better choices of ICs for future particle integration studies.

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