SF2A 2010
S. Boissier, M. Heydari-Malayeri, R. Samadi and D. Valls-Gabaud (eds)

DYNAMICAL MODELING OF THE GALAXY AND STELLAR MIGRATION IN THE DISK

B. Famaey[1] and I. Minchev[2]

Abstract. We exhibit the local and global effects of the non-axisymmetry of the Milky Way potential. In addition to creating moving groups in the Solar neighborhood, we show that spiral structure interacting with a central bar is an effective mechanism for mixing the whole stellar disk radially. This spiral-bar resonance overlap mechanism accounts for the absence of age-metallicity relation in the solar neighborhood, can create extended disks in both Milky Way-mass and low-mass galaxies, and could also be responsible for the formation of a thick disk component early-on in the Galaxy evolution.

Keywords: galaxy: kinematics and dynamics, galaxy: evolution

1 Introduction

Our Milky Way Galaxy is a unique laboratory in which to study galactic structure and evolution. The story of the efforts to obtain stellar kinematic data nicely illustrates how theoretical progress and data acquisition have to go hand in hand if one wants to gain insight into the structure and history of the Galaxy. Until recently, most observational studies have been limited to the solar neighbourhood. The zeroth order approximation for modelling these kinematic data assumes an axisymmetric model, in which the Local Standard of Rest is on a perfectly circular orbit. However, the local velocity field in the solar neighbourhood already displays signatures of the non-axisymmetry of the Galactic potential in the form of stellar moving groups containing stars of very different ages and chemical compositions (Famaey et al. 2005, 2007, 2008), the most prominent being the Hyades stream, the Sirius stream, and the Hercules stream (see Fig. 1 left panel). Here we investigate how to reproduce these streams with a bar and a spiral pattern, and how the combined effect of the bar and the spiral can cause radial migrations in the disk. Future astrometric and spectroscopic surveys will allow radical progress in our understanding of these effects of the non-axisymmetry of the Galactic potential.

2 Moving groups

Kalnajs (1991) suggested that the bar could cause the velocity distribution in the vicinity of the 2:1 outer Lindblad resonance (OLR) to become bimodal, due to the coexistence of orbits elongated along and perpendicular to the bars major axis. Today, we know that this mechanism does account for the Hercules stream (Dehnen 2000) as well as for some low-velocity streams such as the Pleiades (Minchev et al. 2010a). Quillen & Minchev (2005) also showed that the 4:1 ultra-harmonic (or second order) ILR of a 2-armed spiral structure* splits the velocity distribution into two features corresponding to two orbital families, one of them consistent with the Hyades. Test-particle simulations of a stellar disk consistent with the Milky Way kinematics, perturbed by a 2-armed spiral pattern (simulation parameters can be found in Minchev & Quillen 2007) showed that we could indeed reproduce the position of the Hyades stream in velocity-space only when the Sun is near the 4:1 ILR. The beauty of this simulation is that, while reproducing the Hyades stream, the other orbital family creates another remarkable feature in velocity space around $(U, V) \approx (10, 0)$ km/s, which is consistent with the Sirius stream (see Fig. 1, right panel). In order to reproduce the observed streams, the Sun should thus be at the same time close to the 2:1 OLR of the bar and 4:1 ILR of the spiral pattern. Since it has long been known that in the case of resonance overlap the last KAM surface between the two resonances is destroyed, resulting in chaotic behaviour, we expect that such a resonance overlap could give rise to radial migration of stars in the disk.

[1] Observatoire Astronomique, Université de Strasbourg, CNRS UMR 7550, F-67000 Strasbourg, France
[2] Astrophysikalisches Institut Potsdam, An der Sterwarte 16, D-14482 Potsdam, Germany

*Observations indicate that the Milky Way has a 4-armed structure, but with 2 more prominent arms

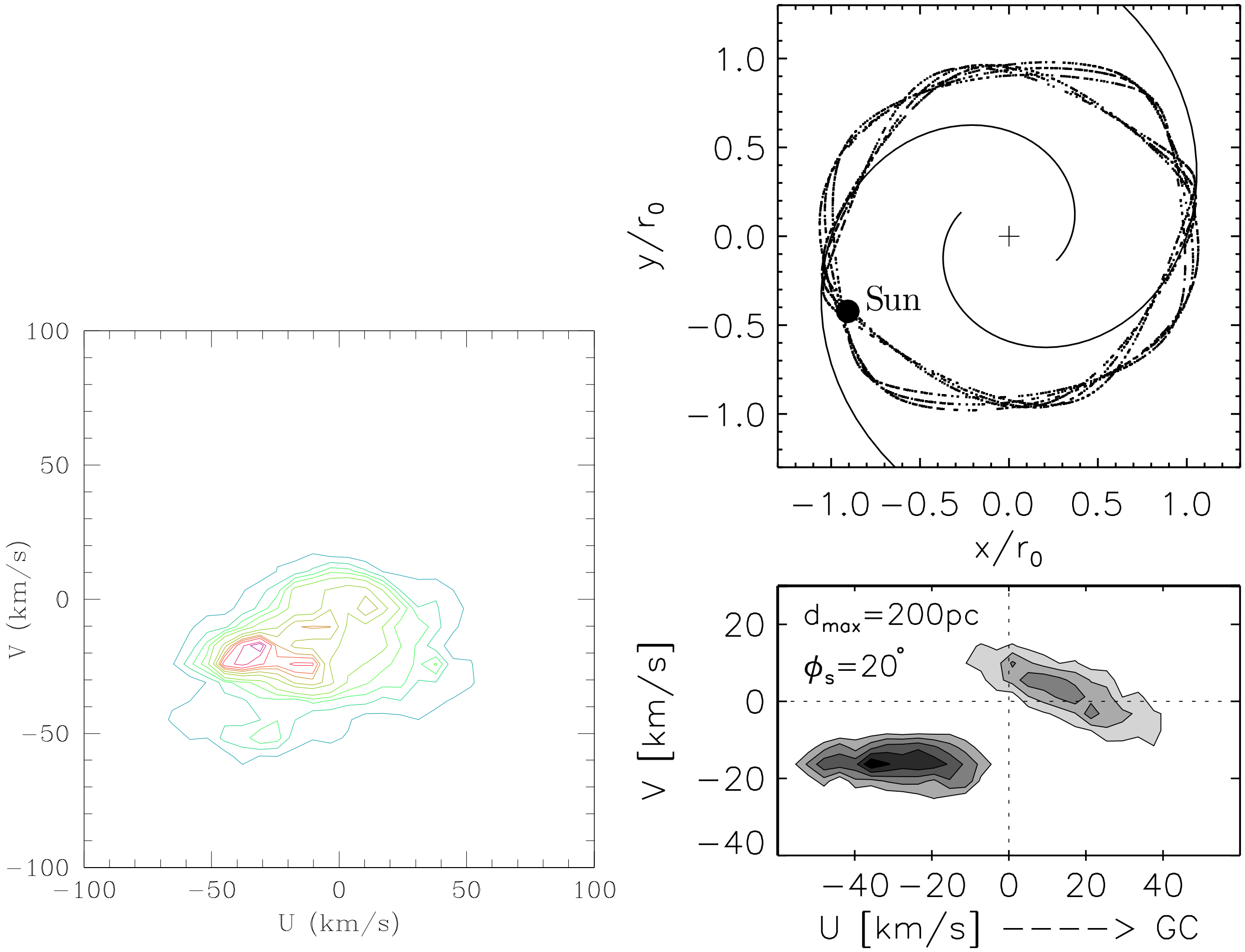

Fig. 1. Left Panel – Isocontours for the Geneva-Copenhagen survey (see Famaey et al. 2007) in the UV-plane (U is the velocity w.r.t. to the Sun in the direction of the Galactic center and V in the direction of Galactic rotation): the contours correspond respectively to 0.5, 0.8, 1.2, 1.5, 1.9, 2.6, 3.1, 3.5, 3.8, 4.2, 4.7, 5. stars/(km/s)^2. The Hyades stream, at $U \simeq -40$ km/s and $V \simeq -20$ km/s, and the Sirius stream at $U \simeq 10$ km/s and $V \simeq 0$ km/s are prominent features. The Pleiades stream is also visible at $U \simeq -15$ km/s and $V \simeq -20$ km/s, and the Hercules stream at $V \simeq -50$ km/s. **Top Right panel** – The effect of a 2-armed spiral structure on orbits near the 4:1 ILR. Note the splitting into 2 families of closed orbits in the frame moving with the (trailing) spiral pattern. For a Sun orientation at 20° with respect to a concave arm, both orbital families enter the solar neighborhood stellar velocity distribution (black filled circle). The galactocentric axes are in units of r_0 (the galactocentric radius of the Sun). **Bottom Right panel** – The effect on the UV-plane for the configuration shown in the top panel (selecting test particles in a 200 pc circle around the Sun). Each orbital family gives rise to a stream in velocity space. We can associate the dense clump at $(U, V) \approx (-40, -20)$ km/s with the Hyades and the shallow one at $(U, V) \approx (10, 0)$ km/s with Sirius.

3 Stellar migration

We have subsequently shown (Minchev & Famaey 2010) that a strong exchange of angular momentum indeed occurs when a stellar disk is perturbed by a central bar and spiral structure simultaneously (see Fig. 2). By using test-particle simulations, we confirmed that this effect was due to the overlap of first and second order resonances of each perturber, and showed that the mechanism was efficient throughout the whole disk, as such overlaps happen evrywhere. Beforehand, it was believed that radial mixing was solely caused by transient spirals (Sellwood & Binney 2002). The efficiency of the new spiral-bar mechanism was confirmed in fully self-consistent, Tree-SPH simulations, as well as high-resolution pure N-body simulations (Minchev et al. 2010b, see Fig. 3).

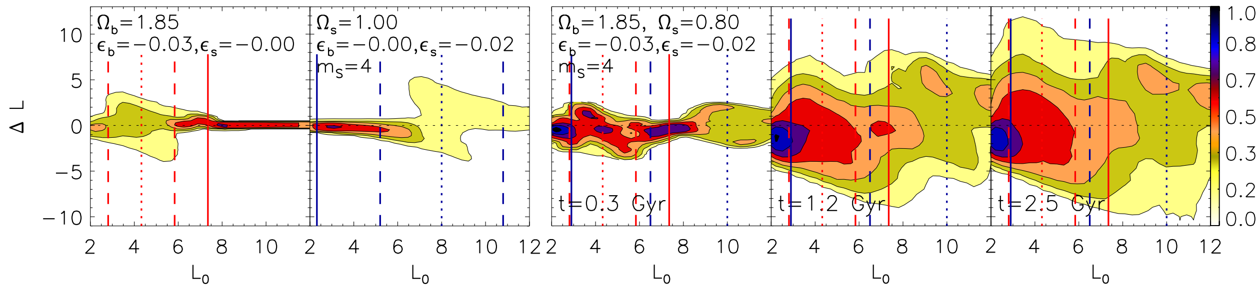

Fig. 2. Changes in the (vertical component of the) angular momentum, ΔL, as a function of the initial angular momentum, L_0. From left to right the first 2 panels show the effect of a bar or a spiral only, respectively, with parameters consistent with the Milky Way. The simultaneous propagation of the same perturbers is shown in the following 3 panels for $t = 0.3 - 2.5$ Gyr. The dotted lines show the corotation radii. The 2:1 and 4:1 LRs are indicated by the solid and dashed lines respectively (bar=red, spiral=blue). Figure is from Minchev & Famaey (2010).

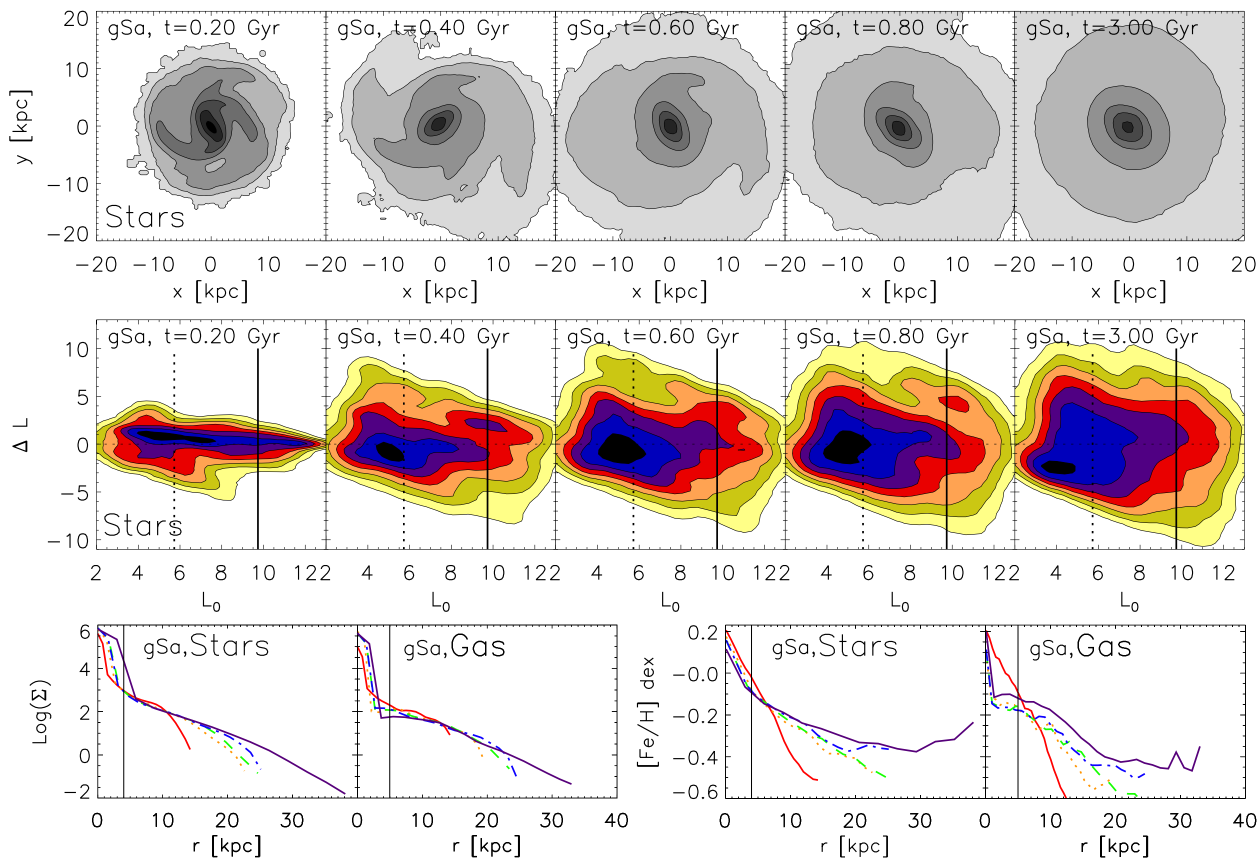

Fig. 3. Results of a Tree-SPH simulation, studying the exchange of angular momentum due to resonance overlap of bar and spiral. **Top row:** Time development of the stellar disk density contours of a giant Sa galaxy. **Second row:** ΔL as a function of the initial angular momentum, L_0. **Bottom row:** The evolution of the radial profiles of surface density (left) and metallicity (right) for the stellar and gaseous disks. The initial disk scale-lengths are indicated by the solid lines. The 5 time steps shown are as in the top row, indicated by solid red, dotted orange, dashed green, dotted-dash blue and solid purple, respectively, from Minchev et al. (2010b).

4 Conclusions

In order to reproduce the local velocity distribution of stars, the Sun should lie close to inner and outer Lindblad resonances of the spiral and bar, respectively. We showed that such a resonance overlap leads to radial migration of stars. This happens throughout the whole disk, as other resonances do overlap too (see Fig. 2). This new theoretical mechanism for stellar migrations could be up to an order of magnitude more effective than the transient spirals mechanism. This effect is non-linear, strongly dependent on the strengths of the perturbers. The signature of this mechanism is a bimodality in the changes of angular momentum in the disk with maxima near the bar's corotation and its outer Lindblad resonance (Figs. 2 and 3). This is true regardless of the spiral pattern speed. This migration mechanism can create extended disks in both Milky Way-mass (Fig. 2) and low-mass galaxies, such as NGC 300 and M33, and it could also be responsible for the formation of a thick disk component early on in the galaxy evolution (Minchev et al., in preparation, see also Schoenrich & Binney 2009). However, important constraints on the mechanism come from the fact that it heats the disk too, and should not overheat it as compared to what is observed. We finally note that the most promising technique to put constraints on this mechanism in the Milky Way is "chemical tagging" (e.g., Bland-Hawthorn et al. 2010) which will become possible with the forthcoming spectroscopic survey HERMES, coupled with the precise astrometric measurements from GAIA.

References

Bland-Hawthorn J., et al., 2010, ApJ, 713, 166
Dehnen W., 2000, AJ, 119, 800
Famaey B., et al., 2005, A&A, 430, 165
Famaey B., et al., 2007, A&A, 461, 957
Famaey B., et al., 2008, A&A, 483, 453
Kalnajs A., 1991, in Sundelius B., ed., Dynamics of Disc Galaxies, Goteborgs Univ., p.323
Minchev I., Quillen A., 2007, MNRAS, 377, 1163
Minchev I., Famaey B., 2010, ApJ, 722, 112
Minchev I., et al., 2010a, MNRAS, 407, 2122
Minchev I., et al., 2010b, arXiv:1006.0484
Quillen A., Minchev I., 2005, AJ, 130, 576
Schoenrich R., Binney J., 2009, MNRAS, 399, 1145
Sellwood J., Binney J., 2002, MNRAS, 336, 785