Highlights of Spanish Astrophysics VIII, Proceedings of the XI Scientific Meeting of the Spanish Astronomical Society held on September 8–12, 2014, in Teruel, Spain. A. J. Cenarro, F. Figueras, C. Hernández-Monteagudo, J. Trujillo Bueno, and L. Valdivielso (eds.)

Dynamical processes in the disk of the Milky Way and Gaia perspective

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Abstract

The dynamics of the disk of our Galaxy is shaped by a complex interplay of processes. For instance, the movement of stars is influenced by the spiral arms and the bar through mechanisms like resonant trapping, scattering and radial mixing. I will review some of these processes and how we model them using controlled simulations. I will also show that these dynamical mechanisms leave strong signatures on the stellar kinematics that we observe today. The models predict over-densities of stars trapped in periodic orbits or non-null mean galactocentric radial velocities at specific positions in the Galaxy, which are not expected in the velocity distributions of an axisymmetric galaxy. As an example, I will show how we have already detected some Galactic bar signatures in the RAVE catalogue, which has allowed us to measure the bar's pattern speed. With ESA's Gaia mission the detection of these signatures will be no longer limited to the Solar vicinity and from these we expect to learn significantly more about the Galaxy's bar and spiral structure, and their effect on stellar orbits.

1 Introduction

In an axisymmetric Galaxy, the stars in the disk follow orbits that describe epicycles around circular orbits. The expected velocity distribution of the stars in the disk in a stationary and axisymmetric Galaxy is expected to be uniform, well-centred and well-aligned with the natural axis of the Galaxy [7] . The blue dots in Fig. 1 (left) show an example of such a distribution.

However, there are several dynamical processes occurring in the Galaxy that may affect this expected velocity distribution due to the induced perturbation on the stellar orbits. For instance,

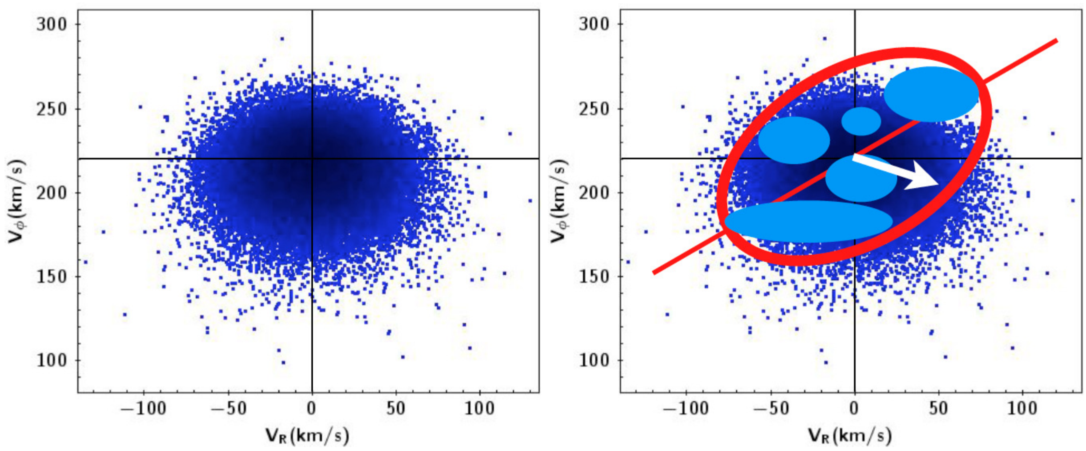

Figure 1: Left: Velocity distribution in the solar neighbourhood of an axisymmetric disk. Right: Effects of the non-axisymmetries of the Galaxy and other dynamical effects on the velocity distribution of the disk. These effects are: i) distributions that are not centred (white arrow), ii) distributions that are tilted (red ellipsoid), and iii) appearance of over-densities (light blue spots).

stars are born in clusters which get disrupted with time due to tidal effects and the interaction with molecular clouds [10]. Satellite galaxies orbiting around our Galaxy also perturb the orbits of stars in the disk [16, 25]. The same satellites can leave behind some of their stars while crossing the disk [20, 33]. Also, the bar and the spiral arms of the Galaxy perturb the orbits of stars in the disk [14, 9, 24, 5, 2].

All these phenomena create characteristic effects on the stellar orbits, which translates into several features that can be seen in the velocity distribution of particular regions of the Galactic disk. The typical effects seen are illustrated in Fig. 1 (right). These effects are: i) distributions that are not centred, ii) distributions that are tilted with respect to the natural axis of the disk (radial, tangential, vertical), and iii) inhomogeneities or appearance of over-densities.

It is important that we detect and measure these features because they tell us directly about the processes taking place in our Galaxy, that is, they allow us to do Galactic archaeology. In this contribution I will review some of these processes and how we model them using controlled simulations. I will also show particular examples of the strong signatures left by these dynamical processes on the stellar kinematics that we observe today and what we have learnt about the Galaxy through the detection of these features. I will discuss about the kinematic substructure and the off-centre velocity distributions. For the tilt of the velocity distribution see [27]. Finally, I will discuss the future perspectives for this kind of studies with the ESA¢¢s Gaia mission.

2 Kinematic substructure, where and why

It is been known since long time that the velocity distribution of the solar neighbourhood is not homogeneous and presents over-densities of different sizes and shapes [23, 8]. The Geneva-Copenhagen survey (GCS) [21] of radial velocities together with astrometric data from Hipparcos ([22]; ESA

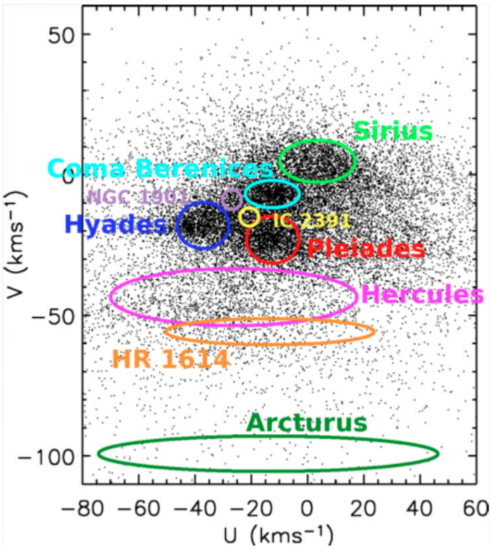

Figure 2: Velocity distribution of the solar neighbourhood using Hipparcos proper motions and parallaxes together with radial velocities from the Geneva-Copenhagen survey. The main know over-densities are shown.

1997) have constituted the largest ($\sim$ 14000 stars) and most precise observational sample of the local ($\sim$ 150 pc) kinematics until quite recently. Figure 2 shows the velocity distribution of the solar neighbourhood using this sample, based on the analysis of [1]. It is visible from this figure that the distribution is not uniform and shows several over-densities, sometimes called moving groups. The main ones are indicated with coloured circles.

The stars in some of these over-densities do not share a common age or metallicity [11, 1], indicating that these over-densities are not remnants of stellar clusters. Other dynamical phenomena must explain the existence of these groups, sometimes called dynamical streams. As explained in Section 1 the spiral arms and the bar can create moving groups as it has been shown by several simulations as well as by analytical perturbation theory [5, 2, 17].

Recently, a new survey has allowed us to discover that these over-densities are present not only in the solar vicinity but also farther from the Sun [3]. The RAdial Velocity Experiment (RAVE) [30] is a multi-fiber spectroscopic survey in the 1.2−m UK Schmidt Telescope in the Anglo-Australian Observatory. The RAVE collaboration is formed by researchers of $\sim$ 20 different institutions and it is coordinated by the Leibniz-Institut fur Astrophysik Potsdam. In total RAVE measured more than 500000 spectra, providing radial velocities with precisions of $\sim 2\,\mathrm{km/s}$ and also stellar parameters, elemental abundances and spectro-photometric distances [6]. The RAVE data has also been combined with proper motions from other catalogues such as UCAC4 [34], Tycho-2 [13] and PPMXL [28]. The last data release DR4 [15] contains 6d phase-space coordinates for around 3.5×10^5 stars.

More in detail, in [3] we detected significant kinematic over-densities in velocity distributions that are $\sim$ 1 kpc from the Sun in the direction of anti-rotation inside the solar circle, in the solar circle and outside the solar circle, and also at $\sim$ 0.7 kpc below the Galactic plane (see figure 3 in [3]). To detect the over-densities we used a technique based on the wavelet transform. We found that the main local kinematic groups were also seen in these samples far from the Sun, and therefore, they must be large-scale features. This was the first confirmation of the existence of moving groups far from the local vicinity.

3 "Tele-measuring" the pattern speed of the bar

In [3] we also found that the main groups in the distributions far from the Sun appear shifted in the velocity plane compared to the local velocity distribution. The clearest example was the Hercules stream that has a larger azimuthal velocity for regions inside the solar circle and a lower value outside. This group is believed to be caused by the effects of the outer Lindblad resonance of the Galactic bar and in fact, test particle simulations of this group also show a similar behaviour [9, 4].

We have modelled analytically the azimuthal velocity of Hercules as a function of position in the Galaxy and its dependence on the bar's pattern speed Ω_b and orientation (angle of the bar with respect to the line Sun-Galactic Centre) ϕ_b. By fitting this model to the RAVE data we have been able to measure properties of the bar using stars that are far from it but trapped into its resonances. We have seen that the likelihood function is highly correlated between the pattern speed and the orientation with a linear relation $\Omega_b/\Omega_0 = 1.91 + 0.0044 \times (\phi_b(\mathrm{deg}) - 48)$, with standard deviation of 0.02, where Ω_0 is the local circular frequency. For an angle of $\phi_b = 30\,\mathrm{deg}$ the pattern speed is $54.0 \pm 0.5\mathrm{km\,s^{-1}\,kpc^{-1}}$ [4].

4 New causes of substructure in the thick disk

Most of the moving groups seen in the thick disk have been normally related to accreted stars from satellite galaxies. This is the case of the moving group of Arcturus [20]. However, this same group has also been hypothesised to be due to the effects of the Galactic bar based on the measured chemical abundances of its stars [31].

The test particle simulations of [18, 17] have shown that, indeed, the Galactic bar can produce over-densities of stars due to resonant trapping and scattering in the thick disk as well as in the thin disk. In fact, the simulations show that the amount of stars trapped in resonances is very similar in both disks (Monari et al., in prep) being around 16% of the stars in the simulated solar neighbourhood. Most of these stars are trapped to the OLR of the bar (80%). These fractions remain roughly constant with height from the plane up to at least 2 kpc. This study establishes a new cause of kinematic substructure in the thick disk: the Galactic bar can produce kinematic over-densities in the thick disk.

5 The wobbly Galaxy

Recently [29] has discovered the existence of a large-scale gradient in the mean radial velocity of stars in the Solar surroundings with RAVE data. More in detail, these authors found a radial gradient of $\sim 3\,\mathrm{km/s\,/\,kpc}$ in the radial velocity, in the sense that stars inside the solar circle move on average radially outwards and stars outside the solar circle move inwards. This would not be expected in a stationary and axisymmetric Galaxy. In that case one would measure always null mean radial velocities. Another study [32] has also shown that there is a vertical gradient in the vertical velocity as well ("the wobbly Galaxy").

Again all these features could be associated to the effects of non-axisymmetries of the disk. For instance, the spiral arms can cause very similar velocity gradients [12], allowing a fit of the spiral arms properties that best reproduce the observations. Models with a bar seem to reproduce the radial gradient but not the vertical one [19].

6 Gaia perspective

The Gaia mission will provide us with a sample of Galactic stellar kinematics that is orders of magnitude better in terms of quantity of stars, spatial extension and precision compared to Hipparcos, GCS or RAVE. For instance, Gaia will give us kinematics for 7.3×10^8 stars in the thin disk and 2.4×10^8 in the thick disk [26]. The typical distances of stars are between 10 and 100 times better depending on the spectral type compared to the $\sim$ 150 pc and 1 kpc of GCS and RAVE, respectively. The precision also depends on spectral type and distance. As an example, the transverse velocity precision for a G0V stars at 1 kpc will be of $\sim 1\,\mathrm{km/s}$ while this will be of $\sim 3\,\mathrm{km/s}$ for a K5III stars at 3 kpc.

These new data set will allow us to study kinematic substructure up to 5 kpc while with RAVE this was up to 1 kpc. From this we expect to measure and constrain other properties of the unknown spiral structure and bar, as well as to infer some aspects of their evolution in time. To definitively confirm that the kinematic groups seen in the thick disk are either of resonant origin or accreted (extra-Galactic) origin, a combination of Gaia measurements and chemical composition provided by Gaia follow-up surveys such as the Gaia-ESO survey or WEAVE will be required. The measurement of velocity gradients in the disk will be carried out up to much larger distances. This will be an exciting period when possibly other new kinematic features and dynamical phenomena will be detected, unravelling the large complexity of our Galaxy and its history.

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