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SOLAR NEIGHBOURHOOD KINEMATICS BASED ON THE GAIA DATA

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Abstract. From GAIA catalog we have selected a sample of stars within 100 pc from the Sun. To avoid sample biases a special concern was taken in regard to radial velocities and multiplicities. We have selected those with necessary data − direction, parallax, proper motion and radial velocity. The kinematics of this sample is analysed. The sample size is 62,598 stars. Using an analytic model of Galactic gravitational potential the galactocentric orbits of these stars are calculated. It is shown, as can be expected, that in the Solar neighbourhood stars mostly belong to the thin disc (86.3%). This is followed by the thick disc which has a fraction of 12.4%, whereas the lowest fraction belongs to the halo (1.3%). The kinematical similarity for suspected binaries is also examined.

1. INTRODUCTION

There is now almost a consensus that, at least as stars from the solar neighbourhood are concerned, the following distinction - thin disc, thick disc and halo - is possible. Classification of particular star in such a manner is usually based on kinematics. To this end one could use merely the velocity components, but also study the motion of individual stars with respect to the centre of the Milky Way, which means to calculate its orbit. Orbit calculation requires reliable data, such as parallax, proper motion and radial velocity. After the Hipparcos Catalogue the progress in astrometric data has become evident. At present thanks to the GAIA Catalogue (Gaia Collaboration et al. 2018) proper motions and parallaxes are available for a vast number of neighbouring stars. The radial velocity data are more scarce. Nevertheless, even within rather small volumes it is possible to find many stars possessing necessary data of sufficiently high quality.

The experience concerning detecting objects of similar kinematics in other astronomical fields, say minor planets in the Solar System (Milani et al. 2014), indicates the importance of the approach based on orbit calculation. To be more clear, it is well known that stars of the thin disc are expected to be always sufficiently near the Galactic plane and also not exhibiting significant changes in their distance to the Galactic axis of symmetry.

In this way we can determine the fractions of the three groups within an unbiased sample of stars, as well as the basic kinematical parameters, such as the mean motion, velocity dispersion, etc. It is also of interest to examine stellar multiplicity for sample member. This offers the possibility of comparing star pairs attributed to either of the two discs to those classified to belong to the halo.

2. SELECTION OF DATA AND METHOD OF ANALYSIS

In this section we describe how we have formed the sample of stars from GAIA DR2 data. At the beginning of 2018, the ESA's Gaia mission produced the second data release Gaia DR2. Gaia DR2 provides position, parallax and proper motions for about 1.3×10^9 stars in the Milky Way (Lindegren et al. 2018), and radial velocity for about 7.2 million stars (Soubiran et al. 2018) measured using a Radial Velocity Spectrograph.

We used two criteria to obtain our sample of stars from the Solar neighbourhood. First we have selected all the stars that have parallax greater than 10 mas. Then, from these sources we have selected those that satisfy the two following conditions: the astrometric parameters are solved and for every source the radial velocity is given. In this way we have obtained a sample of stars, in the solar neighbourhood with distance smaller then 100 pc, consisting of 74,339 stars.

The next step was to remove contamination factors as many as possible. First we considered sources with poor astrometric solutions, but such are expected for Gaia sources that have small parallaxes, so they should not present a potential contamination of our sample. A much more complicated case is with stars that have poorly defined radial velocities. The ESA-Gaia website[1] contains information on a potential radial velocity problem found by Boubert et al. (2019). They cut Gaia DR2 sources with a radial velocity that have a companion in the full Gaia DR2 catalogue within 6.4 arcsec that either itself has a radial velocity or that is brighter in GRP or G magnitudes. The resulting list of 70,365 Gaia DR2 sources with potentially contaminated radial velocities are available in the published paper. The Gaia Radial Velocity Spectrometer team is investigating the issue further in order to improve the Gaia pipeline for future releases. The Gaia team announced that only about 4000 sources have erroneous radial velocities. Among the erroneous ones are e.g. all cases where the Gaia DR2 radial velocity (absolute value) is more than 625 km/s. They also announced that these 4000 erroneous cases will not be copied over to Gaia EDR3, while every other radial velocity entry will be copied from Gaia DR2 to Gaia EDR3. A new set of radial velocities, with improved precission, will be provided as part of Gaia DR3 release.

Then, we clear our sample from multiple stars, because stellar multiplicity can be the case of large errors when calculating orbits. In order to do that, we checked for each star from our sample whether it is contained in the Washington Double Star Catalog, WDS[2]. This process of cross-identification will be explained in more detail in the full account of this research. Our final sample consists of 62,598 stars.

In order to determine galactocentric orbits we used the model of the Milky Way potential proposed by Ninković (1992). This model assumes three contributors to the potential of the Milky Way: the bulge, the disc, and the corona (the subsystem consisting of dark matter). The latter is assumed as spherically symmetric, while

[1] https://www.cosmos.esa.int/web/gaia/dr2-known-issues#RadialVelocitiesCrowdedRegions
[2] http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds

the other ones are assumed to be axisymmetric. The contributions to the Galactic potential of the former two are described by the same formula, that of Miyamoto and Nagai (1975). The only difference concerns the values of the model parameters. The values of model parameters are obtained on the basis of the model constants, which are assumed a priori. The data from Gaia DR2 (five-parameter astrometry solution and radial velocity) are used as input for the model. The integration of the galactocentric orbits for each star is done for 10 Gyr by using a 4th order Runge Kuta method. In this way, the values for various quantities were obtained, but for the purpose of segregation we use only z_{min} and z_{max}; $|z|$ is the distance from the Galactic plane.

Since the input data are given in the equatorial spherical reference system, it is necessary to transform them into the heliocentric Cartesian system in which the coordinate axes are along the Galactic coordinates. Furthermore, the obtained heliocentric Cartesian velocity components should be corrected for the Solar motion. Usual designations are adopted:

U direction towards Galactic centre: $l = 0°$, $b = 0°$;

V direction of Galactic rotation: $l = 90°$, $b = 0°$;

W direction towards the north Galactic pole: $b = 90°$.

Their values are used for the purpose of the segregation in addition to z_{min} and z_{max}.

3. DISCUSSION AND RESULTS

According to the Boubert (2019) we have removed the stars with problematic radial velocities. In our sample of 74,339 stars we found 9,891 stars that should be removed in order to get a better quality of our sample. Top panel in Fig. 1 shows our sample of stars including those stars that have been removed due to radial velocity contamination. The abbreviation LSR means that the velocity components are with respect to the local standard of rest.

We identified 9905 stars from our sample in the WDS catalogue, and then we checked for each of them whether it is possibly a multiple star, by comparing its radial velocity, magnitude and parallax. In total, we found 3200 stars belonging to possible binary systems (1600 pairs), and we found 69 to belong to possible triple systems (23 systems). For the remaining 6636 stars from WDS, we have the required data from Gaia for only one of the system components. Middle panel in Fig. 1 shows these 3269 stars that were removed from our sample. Bottom panel in Fig. 1 indicates the correlation between stellar multiplicity and radial velocity contamination. This is a good indicator showing that multiplicity of stars can potentially make a problem for radial velocity determination.

We found for some well known binaries that the components have significantly different galactocentric orbits. There are examples where for a binary we can find in the Sixth Catalog of Orbits of Visual Binary Stars, ORB6[3] orbital elements of sufficient quality, but nevertheless for the components we obtain different galactocentric orbits. Most likely this is due to unreliable parallax, radial velocity or proper motion measurements. Two examples are shown in Fig. 2: first row - `WDS 06048-4828 = DUN 23` and second row - `WDS 21008-0821 = BU 678`. On the left panels of this figure we can

[3]http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/orb6

see galactocentric orbits of the primaries, while on the right panels we see the secondaries. Title of each panel is Gaia DR2 source id. In the case of such measurements the motion of mass centre can cause significant errors. Parameters from Gaia DR2 for these four stars are presented in Table 1. These four stars, among others, are removed from our sample.

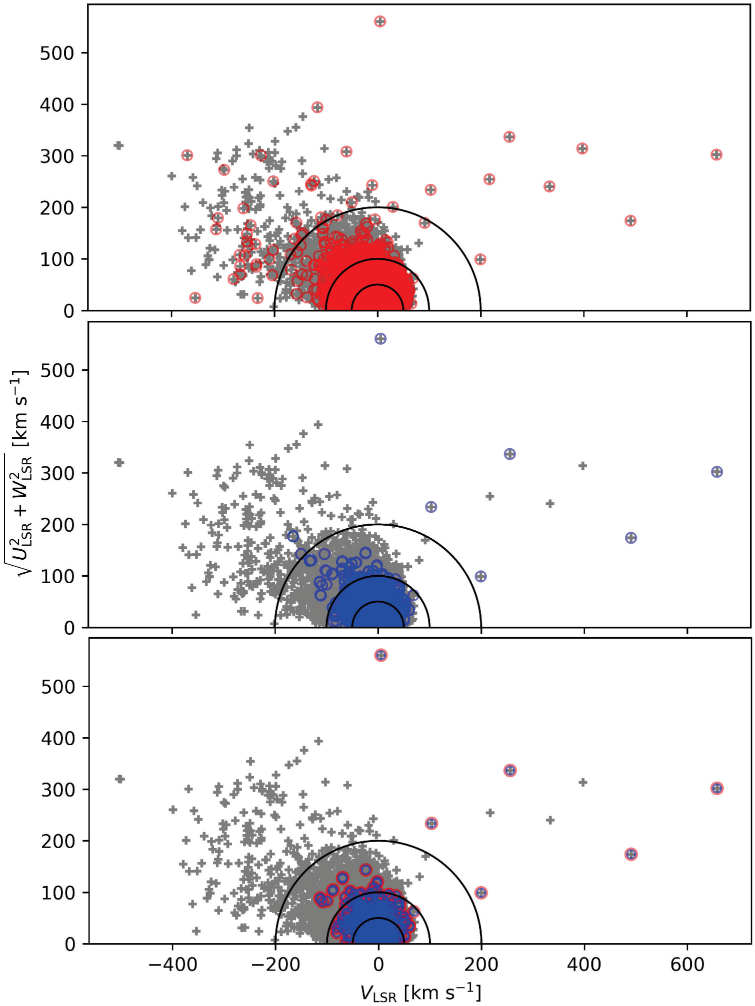

Figure 1: Toomre diagrams showing the stars from our sample (gray cross) and those removed due to: contamination in the radial velocity (top panel), multiplicity (middle panel), both criteria (bottom panel). Semicircles (black lines) represent $|V_{LSR}|$ less than or equal to 50, 100 and 200 km s^{-1}, respectively.

Finally our sample of Gaia DR2 sources consists of 62,598 stars. In our kinematical approach for defining which star belongs to which component of the Galaxy we used the following segregation method. This method originates from our previous studies (Ninković et al. 2012, Stojanović 2015, Cubarsi et al. 2017).

Table 1: Parameters from Gaia DR2 for four stars presented in the Fig 2.

WDS id	l	b	Gaia_source_id	π	err	μ_α	err	μ_δ	err	V_r	err
DUN_23_P	091.19470494847	–48.45883408526	5554191685019290368	32.47	0.02	–117.38	0.05	–39.04	0.04	14.25	0.17
DUN_23_S	091.19383987985	–48.45839608168	5554191685020871424	32.51	0.03	–101.11	0.06	–22.69	0.06	35.24	5.25
BU_678_P	315.20448826514	–08.34289191004	6908757299968653440	29.11	0.04	227.12	0.07	46.77	0.05	–34.26	1.14
BU_678_S	315.20527437965	–08.34275522474	6908757299969652480	29.15	0.04	237.94	0.08	26.74	0.05	–35.96	0.15

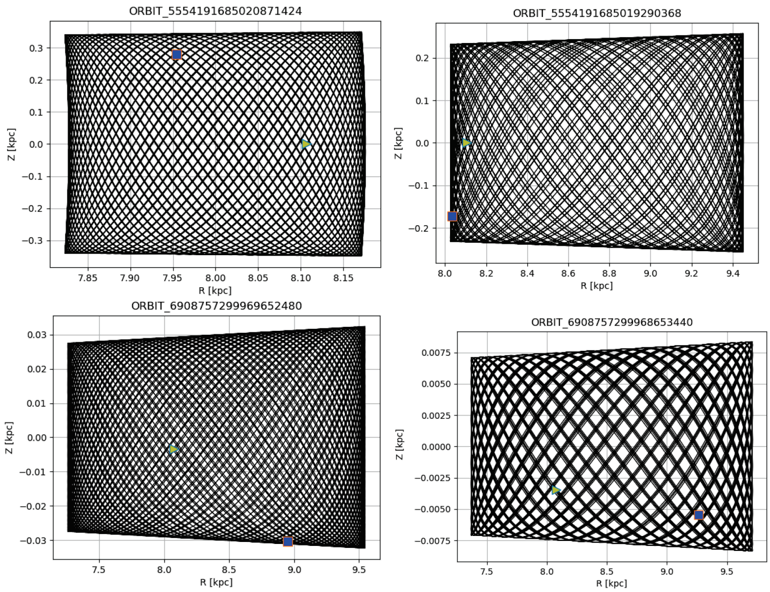

Figure 2: Binary systems: first row - `WDS 06048-4828 = DUN 23` and second row - `WDS 21008-0821 = BU 678`; primary components - left panels, secondary components - right panels. Triangle is starting point of integration which is actually input from Gaia DR2, blue square is end point in integration. Panel titles are Gaia DR2 source ids. Integration time 10 Gyr.

First we select those stars that satisfy the following three conditions:

$$-110 \text{ km s}^{-1} \leq U \leq 90 \text{ km s}^{-1};$$
$$-80 \text{ km s}^{-1} \leq V \leq 40 \text{ km s}^{-1};$$
$$z_{\text{min}} \geq -0.5 \text{ kpc} \quad \& \quad z_{\text{max}} \leq 0.5 \text{ kpc}.$$

These stars should belong to thin disc. The selection is thus based on the speed of a star with respect to LSR and its maximum distance from the Galactic plane. The number of stars for which this condition is satisfied is 54,033 (86.3%). Next, in the case of the halo it is enough that a star fulfils one of the following conditions:

$$U \leq -210 \text{ km s}^{-1} \quad \text{or} \quad U \geq 190 \text{ km s}^{-1};$$
$$V \leq -130 \text{ km s}^{-1} \quad \text{or} \quad V \geq 70 \text{ km s}^{-1};$$
$$z_{\text{min}} \leq -1.5 \text{ kpc} \quad \text{or} \quad z_{\text{max}} \geq 1.5 \text{ kpc}.$$

The number of such stars is 784 (1.3%). At the end of this process the remaining stars should belong to the thick disc. Their number is 7781 (12.4%). The results of

Table 2: Components of our Galaxy with the number of stars, percentage, mean motion ($\overline{U}$, $\overline{V}$, $\overline{W}$) and random velocity matrix for each component.

Component	Number	Percentage	Mean motion		Random velocity matrix		
Thin Disc	54033	86.3	$\overline{U}$	–9.6	1036.13	118.53	6.03
			$\overline{V}$	–18.4	118.53	419.01	5.76
			$\overline{W}$	–6.7	6.03	5.76	158.23
Thick Disc	7781	12.4	$\overline{U}$	–11.47	2758.04	224.45	–69.18
			$\overline{V}$	–33.72	224.45	1428.73	–1.33
			$\overline{W}$	–13.99	–69.18	–1.33	1376.97
Halo	784	1.3	$\overline{U}$	–13.45	11353.33	–640.23	–79.77
			$\overline{V}$	–116.90	–640.23	8101.03	–763.08
			$\overline{W}$	–14.69	–89.77	–763.08	5659.85

this selection of stars according to the defined kinematical properties are presented in Table 2, together with the mean motion ($\overline{U}$, $\overline{V}$, $\overline{W}$) and random velocity matrix for each component.

4. CONCLUSION

Our first objective is to form an unbiased sample of nearby stars. The purpose is to study the local kinematics. We find that the GAIA data still have errors. Inter alia in the case of some already confirmed binaries (inner motion evaluated with high grades) our calculation of galactocentric orbits for each binary component individually, gave unrealistic values! Of course, such a result in our opinion is due to the data errors, in particular, in parallax, radial velocity and proper motion. So we find additional criteria to avoid including stars with doubtful data in the final sample. By comparing the initial sample size with the final one we find that almost 16% of stars had to be excluded. In the final sample following our established segregation criteria we have for the fractions: thin disc 86.3%, thick disc 12.4% and halo 1.3%.

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