From Nearby Stars to Solar Kinematics: New Insight from Gaia DR2 Catalogue

Rendy Darma[1] and Wulandari[1]

[1]Astronomy Study Program, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Indonesia 40132

[a]darmarendy@gmail.com

Abstract. The motion of stars has an important role in understanding the kinematics and dynamics of celestial phenomena in the galaxy. In the present day, the new up to date stars catalogue from Gaia DR2 has provided new insight in the context of stars kinematics in the Galaxy. We attempt to analyze the FGK Main-Sequence nearby stars from Gaia DR2 catalogue to investigate the Solar kinematics. A data reduction and analytic classification are implemented in this work to obtain the well-selected stars. Our calculation shows that the Solar kinematics is typically $(u_{\odot}, v_{\odot}, w_{\odot})$ = (15.136 ± 0.408, 11.454 ± 0.481, 8.899 ± 0.163) km/s after being corrected with asymmetric drift V_a = (8.261 ± 0.160) km/s for a typical position according to our selected stars in this work.

1. Introduction

The motions of stars provide vital information regarding most of the phenomena in a whole galaxy. Previous studies (see [1], [2], [3], [4], [5]) have been done to investigate the existence of a supermassive black hole at the Galactic center, by understanding the motions of stars at that region. Furthermore, the understanding of stellar motions in the halo Galactic region also provides strong evidence of dark matter in the Galaxy [6], [7]. Measuring the stellar kinematics in the Galaxy is relatively easy in this era, due to the availability of instruments with highly precise measurements (e.g., Gaia mission, Hubble Space Telescope, SDSS), that is providing catalogues with a high level of precision. From the stellar kinematics, we should also be able to investigate the Solar kinematics in our Galaxy, which is also the fundamental property to study the kinematics and dynamics of other stars and our Galaxy.

To understand the Solar kinematics in our Galaxy, we need to understand the motion of the Sun with respect to the Local Standard of Rest (LSR). The LSR is an imaginary rotating reference that resides around the Sun and orbiting the Galactic center with a perfectly circular orbit $(u_{LSR}, v_{LSR}, w_{LSR})$= (0.0, 220, 0.0) km/s. The velocity in UVW direction will be explained in Section 2.2. The Solar kinematics determination still becomes a hot issue, particularly for $v_{\odot}$. Furthermore, the stellar motions in the direction of galactic rotation tend to lag to the LSR, called as asymmetric drift which depends upon the velocity dispersions of the certain stellar population [8]. The younger population has a smaller velocity dispersion than the older ones [9], [10], [11], [12]. Besides, [13] studied the relation between the Solar velocity relative to the stars (v) and velocity dispersions (S) versus color. They pointed out that a trend both V and S systematically increase from early to late spectral types.

Due to the lack of information about asymmetric drift, many studies tried to solve this issue by applying various methods (see [8], [12], [13], [14], [15], [16]). In this work, we are attempting to determine the Solar kinematics in the context of its space velocity in our Galaxy, by considering the effect of asymmetric drift. Stars around the Sun are predominantly FGK Main-Sequence stars in which their motions are well known within 100 pc from the Sun. We use these selected FGK Main-Sequence stars from Gaia DR2 Catalogue to accommodate the calculation of Solar space velocity. In Section 2, we present the data and method used in this work. The result and analysis are coupled in Section 3. Finally, the conclusion is presented in Section 4.

2. Methodology

To understand the Solar space velocity, we need to analyze the kinematics of stars around the Sun. It is a challenging effort because we need to collect the whole stars around the Sun. Fortunately, we recently have a new up to date and highly precise data of stars in our Galaxy, containing a million of stars within it, i.e. Gaia catalogue, in which now in the stage of second data release (DR2). In 2021, the third data release which also accommodates the spectral information will be released. In this work, we will present the data reduction process implemented and the solar space velocity calculation. We use the Python programming language to do this reduction and calculation process. The codes can be accessed here.

Table 1. The photometry, astrometry, and kinematic parameters of the selected stars.

Parameter	Data	Used to
Photometry	Color index ($G - G_{BP}$) Color index ($G - G_{RP}$) Color index ($G_{BP} - G_{RP}$)	Classify the FGK Main-Sequence stars.
Astrometry	Right ascension (α) Declination (δ)	Calculate stars velocity relative to the Sun.
Kinematic	Parallax (ρ) Proper motion (μ) Radial velocity (V_r)	

2.1. Data and Data Reduction

In this work, we use photometry, astrometry, and kinematic parameters of the stars selected from Gaia DR2 Catalogue (see [17], [18], [19]). Table 1 presents the detailed parameters of every star used in this work. The sample of stars must satisfy the following criteria:

1. The stars must be within 100 pc from the Sun due to our concern in Solar neighborhood stars in the thin disc Galaxy. At such radius from the Sun, we also can avoid the effect of interstellar reddening [20].
2. The relative errors of the astrometric and kinematic parameters must not exceed 10% to obtain the stellar velocity more precisely.

According to the aforementioned criteria, we obtain 52711 stars from Gaia DR2 Catalogue. In this work, we use only the FGK Main-Sequence stars in order to obtain relatively similar motions with the Sun. There are two ways that we implement to obtain such types of stars samples. Firstly, we implement the Density-Based Spatial Clustering (DBSCAN) algorithm with the smoothing length is 0.03 and the minimum sample is 500. This algorithm is implemented in order to distinguish the Main-Sequence stars and non-Main-Sequence stars within photometry distributions (see Figure 1). From this algorithm, we obtain 49539 Main-Sequence stars.

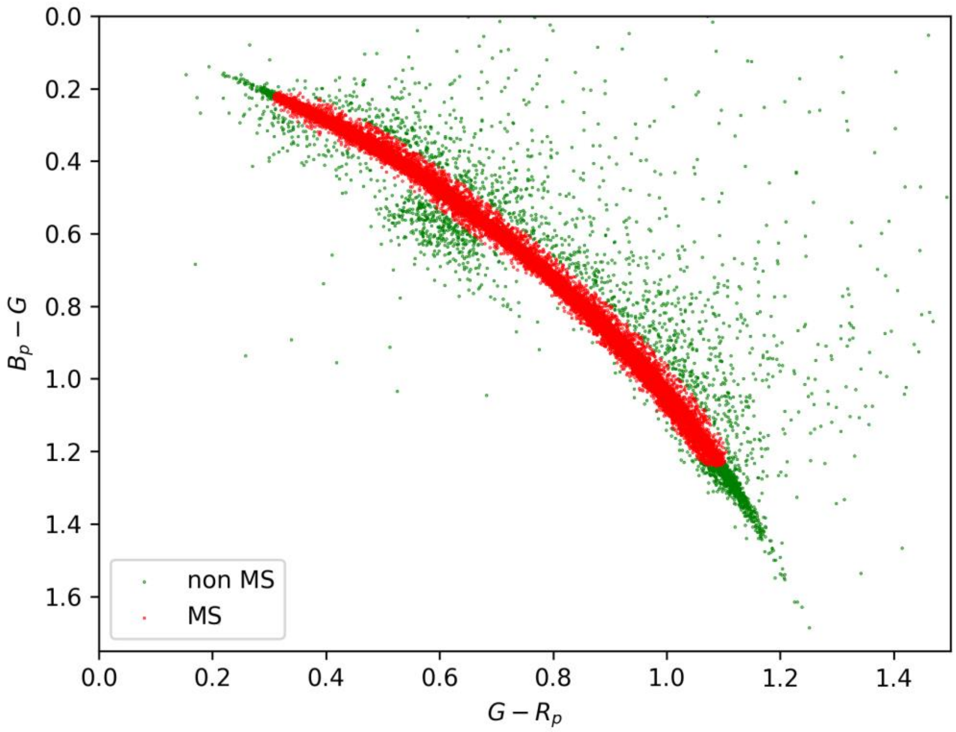

Figure 1. The classification of Main-Sequence (MS, red dots) stars and non Main-Sequence (non MS, green dots) stars using the DBSCAN algorithm. Every dot represents a star with a different evolutionary stage.

Secondly, we need to calculate analytically the effective temperature of the Main-Sequence stars, by following [21] equation, i.e.:

$$T_{eff} = 4600\left(\frac{1}{0.92(B-V)+1.7} + \frac{1}{0.92(B-V)+0.62}\right). \tag{1}$$

The quantity of color index $(B - V)$ can be calculated by solving the Equation (2), (3), and (4) which adopted from [22], i.e.:

$$G - G_{BP} = -0.0160 - 0.4995(B-V) - 0.1749(B-V)^2 + 0.0101(B-V)^3, \tag{2}$$

$$G - G_{RP} = 0.0821 + 0.9295(B-V) - 0.2018(B-V)^2 + 0.0161(B-V)^3, \tag{3}$$

$$G_{BP} - G_{RP} = 0.0981 + 1.4290(B-V) - 0.0269(B-V)^2 + 0.0061(B-V)^3. \tag{4}$$

By combining the three equations, we obtain the relation between $(B - V)$, $(G - G_{BP})$, $(G - G_{RP})$, and $(G_{BP} - G_{RP})$, i.e.:

$$(B-V) = -30.29578793(G - G_{BP}) + 30.19367011(G - G_{RP}) - 29.52957408(G_{BP} - G_{RP}) - 0.0667657186. \tag{5}$$

Here are the effective temperature constraints of each spectral class of FGK stars:

I. F spectral type: $6000\,K \leq T_{eff} \leq 6800\,K$,
II. G spectral type: $5300\,K \leq T_{eff} < 6000\,K$,

III. K spectral type: $4200\,K \leq T_{eff} < 5300\,K$.

According to the aforementioned criteria, we obtain 36573 stars from our samples. This is the final sample we use in this work. We then calculate the space velocity of FGK Main-Sequence stars with respect to the Sun, by implementing a transformation method as suggested by [23]. In general, the method is transforming astrometry and kinematic parameters into UVW space velocities. The UVW velocities of these stars will be used to determine the Solar space velocity in the next step. Note that UVW velocities are the velocities of stars in U (radially inwards the Galactic center), V (in the direction of the Galactic rotation), and W (vertically upwards the Galactic plane) directions.

2.1.1. Solar Space Velocity Calculation. Theoretically, the Solar space velocity in UVW directions ($u_\odot$,$v_\odot$,$w_\odot$) with respect to the LSR can be calculated as follows:

$$u_\odot = \langle u_\star \rangle - \langle U_\star \rangle, \tag{6}$$

$$v_\odot = \langle v_\star \rangle - \langle V_\star \rangle, \tag{7}$$

$$w_\odot = \langle w_\star \rangle - \langle W_\star \rangle. \tag{8}$$

The parameters $\langle U_\star \rangle$, $\langle V_\star \rangle$, and $\langle W_\star \rangle$ are the average stars velocity with respect to the Sun in U, V, and W directions, respectively. The parameters $\langle u_\star \rangle$ and $\langle w_\star \rangle$ are the average stars velocity in U and W directions with respect to the LSR, respectively, in which it can be considered equal to zero due to the LSR is assumed only having a quantity of velocity in V direction. Meanwhile, the average stars velocity in V direction ($\langle v_\star \rangle$) tends to lag the LSR. The lag velocity of the stars with respect to the LSR referred to asymmetric drift (V_a). The Equation (6 – 8) can be rewritten as:

$$u_\odot = \langle u_\star \rangle - \langle U_\star \rangle \;=\; -\langle U_\star \rangle, \tag{9}$$

$$v_\odot = \langle v_\star \rangle - \langle V_\star \rangle \;=\; V_a - \langle V_\star \rangle, \tag{10}$$

$$w_\odot = \langle w_\star \rangle - \langle W_\star \rangle \;=\; -\langle W_\star \rangle. \tag{11}$$

The quantities of parameters $\langle U_\star \rangle, \langle V_\star \rangle$,and $\langle W_\star \rangle$ can be obtained by fitting the stars UVW velocities distributions using a Gaussian function as a simple approximation. The value of asymmetric drift can be analytically calculated using an equation from [12], i.e.:

$$V_a \cong \frac{1}{2V_c}\left[\sigma_V^2 + \sigma_W^2 + R\,\sigma_U^2\left(\frac{1}{R_d} + \frac{2}{R_\sigma} - \frac{2}{R}\right)\right], \tag{12}$$

where R_σ = 13.70 kpc [24] is the scale length of σ_U. The parameter R_d = 2.5 kpc is the scale length of the star density, R is the typical position of the selected stars, and V_c = 220 km/s is the circular velocity at Solar position.

3. Results

Our FGK Main-Sequence stars distribution in position shows that the typical position is at R ~ 8 kpc from the Galactic center. According to such value, the calculated asymmetric drift around the Sun that is given by Equation (12) is V_a = (8.261 ± 0.160) km/s. The Gaussian fittings to the stars UVW velocities distributions have been done (see Figure 2) and providing a result of Solar space velocity, i.e. ($u_\odot$,$v_\odot$,$w_\odot$) = (15.136 ± 0.408, 19.715 ± 0.408, 8.899 ± 0.163) km/s. After corrected with asymmetric drift, the Solar space velocity in V direction becomes $v_\odot$ = (11.454 ± 0.481) km/s. The velocity uncertainties are obtained from the fitting process which implements the Markov Chain Monte Carlo (MCMC) algorithm (see [25], [26], [27]), in the context of standard deviation.

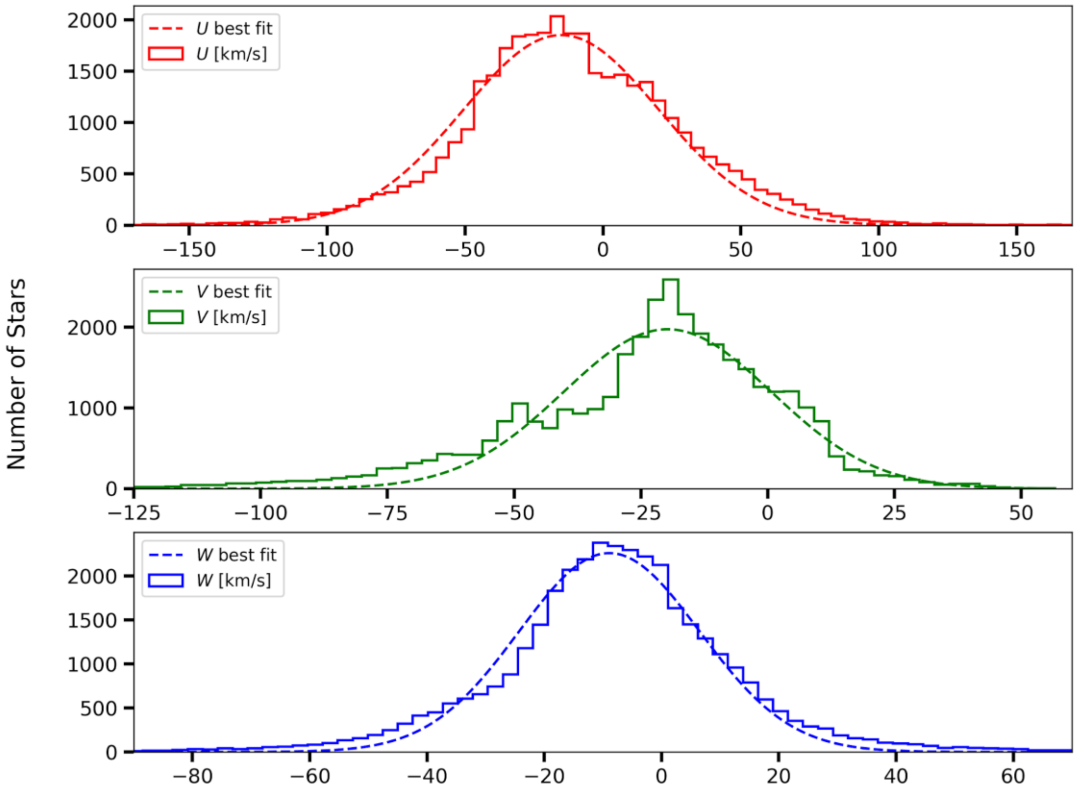

Figure 2. The Gaussian fittings to the stars distributions in UVW velocities. We use the MCMC algorithm in the fitting process.

As comparisons with previous studies, [12] obtained $v_{\odot}$ = (9.75 ± 0.19) km/s and $v_{\odot}$ = (10.37 ± 0.15) km/s by implementing different methods. Furthermore, [8] obtained $v_{\odot}$ = (12.4 ± 2.1) km/s. Our result of $v_{\odot}$ is in a good agreement (within its uncertainties) with those previous studies. However, [13] obtained $v_{\odot}$= (5.25 ± 0.62) km/s, smaller than our result in this work.

The quantity of $u_{\odot}$~ 15 km/s obtained in this work is relatively similar like the calculations of $u_{\odot}$ from [28] with several different methods, i.e. $u_{\odot}$ ~ 13 - 14 km/s. The other results, such as [8] and [12], the quantity of $u_{\odot}$ = (7.01 ± 0.20) km/s and $u_{\odot}$ = 7.25 km/s, respectively, much smaller than obtained in [28] and in this work. A rather different result also obtained by [13], i.e. $u_{\odot}$ = (10.00 ± 0.36) km/s. The calculation of Solar space velocity in W direction obtained in this work ($w_{\odot}$ ~ 8.9 km/s) is a bit larger (within its uncertainties range) than obtained by [8], i.e. $w_{\odot}$ = (7.25 ± 0.5) km/s and [13], i.e. $w_{\odot}$ = (7.17 ± 0.38) km/s. Other results from [12], i.e. $w_{\odot}$ = (4.95 ± 0.09) km/s and [28], i.e. $w_{\odot}$ = (4.96 ± 0.44) km/s, are smaller than our result.

There are several factors that affect the different results of Solar space velocity calculations. The number of data used in the calculation is the main factor that affects the results. The new up to date catalogues of stars (e.g. Gaia, LAMOST, RAVE, SDSS) have been covering more precise data of stars and can be used to improve the Solar space velocity calculations in more precise ways. Another factor is the methods and assumptions used in the calculations will also carry out the differences in results. However, the efforts of calculating the Solar space velocity will always be a challenging effort and we are attempting to provide a new insight of the Solar space velocity in our galaxy. Understanding the Solar space velocity would bring us to understanding the dynamics of the Sun, nearby stars, and our Galaxy.

4. Conclusion

We have done in calculating the Solar space velocity from the FGK Main-Sequence stars within 100 pc from the Sun. The new up to date Gaia DR2 Catalogue has provided more accurate measurement of stellar kinematics around the Sun. Our fitting to the stars UVW velocities distributions result the Solar space velocity is typically ($u_{\odot}$,$v_{\odot}$,$w_{\odot}$) = (15.136 ± 0.408, 11.454 ± 0.481, 8.899 ± 0.163) km/s after being corrected with asymmetric drift, i.e. V_a = (8.261 ± 0.160) km/s. Our result is in a good agreement (within its uncertainties range) to several previous studies, yet also sufficiently different with the previous ones. The number of data, the level of precision of the data, and the assumptions and methods used in the calculations will be the main factors that affect the differences in results. However, through this work, we provide the Solar space velocity calculation from one of the newest up to date stars catalogue, in which the result is still necessary to be confirmed by future studies with the detailed calculation method.

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