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KINEMATICS OF TYPE II CEPHEID PULSATING STARS

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Abstract. In the GAIA Data Release 3 catalogue, published in 2023, there are 15021 stars classified as Cepheids. We will use a sub-sample of stars classified as Type II Cepheids (T2C) from the GAIA catalogue that have all the necessary parameters (full astrometry and radial velocity) to calculate the galactocentric orbits of these stars. For this we will use the analytical potential proposed earlier by one of the authors. We will calculate angular momentum and energy of the stars to determine if they belong to some of the known mergers, as it has been shown that satellite galaxies of the Milky Way can be considered as particles with very similar integrals of motion. We will analyse the distribution of the energy and angular momentum for our sample of stars. It is very likely that most of the T2Cs were created in the Milky Way however, there is a subgroup of T2Cs that have significantly different metallicities than the other stars. This could be an indication that they might have originated from different surroundings, such as a different galaxy, and came to the Milky Way via a merger event. In this work we will examine this possibility.

1. INTRODUCTION

A variable star, in general, is a star (single, binary, or in a multiple system) that is observed by changing its brightness in time. Variable stars can change their brightness due to extrinsic or intrinsic as it is described in Eyer & Mowlavi (2008). In the case of intrinsic variable stars there is further division based on the reason what causes the change inside the stars. A subclass of variable stars that is pulsating in time are called the pulsating variable stars. As the star leaves the Main Sequence of the Hertzsprung–Russell Diagram (an example of this diagram is given in Figure 1) it has spent most of the hydrogen in the core. The fusion process moves to a shell outside the core. The equilibrium between the radiation pressure from the core and the gravity due to the mass of the star is not stable anymore, so it starts to pulsate in a regularly repeating manner. There are many types of pulsating stars, but the most well known are the Cepheid variables. They can be further subdivided.

The Type II Cepheids, which are one of the sub-types of the Cepheid variables, are described as low-mass old pulsating stars. These stars can be found in the Milky Way and surrounding dwarf galaxies, as well as globular clusters, but their number is quite small. They can be separated into three sub-groups according to the period of their pulsation (P) given in days: BL Her stars, $1 < P < 4$, W Vir stars, $4 < P < 20$, RV Tau stars, $20 < P < 100$, see Soszyński et al. (2018). They can be identified by their light curve shapes, for example. They form a period-luminosity relation, so they can be used to anchor the distance scale independently of the classical Cepheids (pulsating giants).

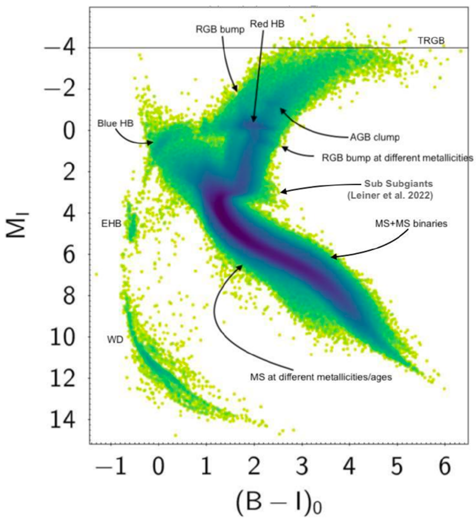

Figure 1: Colour-magnitude diagram generated by combining the Johnson-Kron-Cousins (B-I) colour and the absolute magnitude in the I band, as measured from the Gaia parallax and the Gaia XP spectra using synthetic photometry. The main loci of the stellar evolutions are marked (MS: Main Sequence; RGB: Red Giant Branch; TRGB: Tip of the RGB; AGB: Asymptotic Giant Branch HB: Horizontal Branch; EHB: Extreme HB; WD: White Dwarfs). Image credits: ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: M. Bellazzini. The T2Cs are located above the HB towards the upper limit of the TRGB.

Since Type II Cepheids are old stars we investigated if these stars can trace back to any of the known mergers that happened in the past in the Milky Way during it's evolution. It is known that a massive dwarf galaxy Gaia-Enceladus or Gaia Sausage merged with the Milky Way about 10 Gyr ago which resulted in the formation of many globular clusters and the thick disk Koppelman et al. (2020) and Helmi et al. (2018). To search for these connections we first reconstructed the orbits of individual Type II Cepheids from the Milky Way.

Regarding the Milky Way galaxy, we can assume following distinction of components bulge, disc (probably thin and thick disc) and dark halo (Dehnen & Binney 1998). In order to reconstruct galactocentric orbit of each star in our sample we need position, parallax, proper motion and radial velocity of each star in our sample. At present thanks to GAIA Catalogue (Gaia Collaboration et al. 2023) we have formed a sample of stars that are classifies as T2Cs. Currently in GAIA DR3 there are 1551 stars classified as T2Cs, but only for 64 stars there are radial velocities. This is still very large sample of T2Cs since previously General Catalog of Variable Stars (GCVS) only had data for 7 stars (Jurkovic et al. 2016). Classification of particular star is based on kinematics, where we use velocity components, but also we study the motion of each star in the sample with respect to the centre of the Milky Way, which means to calculate its orbit. In this way, we can determine to which of the components star belongs.

2. METHODS

Here, we use gravitational potential of the Milky Way given analytically to determine galactocentric orbits. This model was proposed by Ninković (1992). This model assumes three contributions to the potential of the Milky Way. The components are: the bulge, the disc and corona (the subsystem consisting of dark matter). The corona is defined as spherically symmetric subsystem, while the other ones are assumed to be axisymmetric. The values of the model parameters are explained in detail in (Stojanović et al. 2018). The data from GAIA DR3 are used as input for the model. The integration of the galactocentric orbits for each star is done for 10 Gyr. In this way, as values for the purpose of segregation of the sample we use z_{min} and z_{max}; where $|z|$ is distance from the Galactic plane. The method for segregation uses kinematic characterisation of the stellar components. This method was well tested and proved to give reliable, but fast, results for segregation (for more details see Cubarsi et al. (2021a), Cubarsi et al. (2021b)).
First we select those stars that satisfy the following three conditions:

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

where velocity components are given with respect to the Sun - as usually U towards the Galactic centre, V along the Galactic rotation and $|z|$ is maximum distance to the Galactic plane attained during the orbital motion. These stars should belong to thin disc. The selection is thus based on the speed of a star with respect to Local Standard of Rest (LSR) and its maximum distance from the Galactic plane. The number of stars for which this condition is satisfied is 7. Next, in the case of the halo it is enough that a star fulfills one of the following conditions:

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

The number of such stars is 38. At the end of this process the remaining stars should belong to the thick disc. Their number is 19. The results of this selection of stars according to the defined kinematic properties are presented in Table 1. This process can further be refined to checking more parameters of each galactocentric orbit separately, like eccentricity, and r_p and r_a peri and apo-centric distance. Further examination showed no outliers and the segregation of the sample stayed the same.

Table 1: Classification of Type II Cepheids according to their orbits.

Milky Way substructure	Number of stars
Thin disc	7
Thick disc	19
Halo	38

3. DATA AND RESULTS

The number of stars that have radial velocity measurements in *Gaia* DR3 data set that were classified as variable stars is 1551. We have searched the gaia.dr3_vari catalog. Among those stars 64 Type II Cepheids were identified by Ripepi et al. (2023). Our sample is shown in Fig. 2.

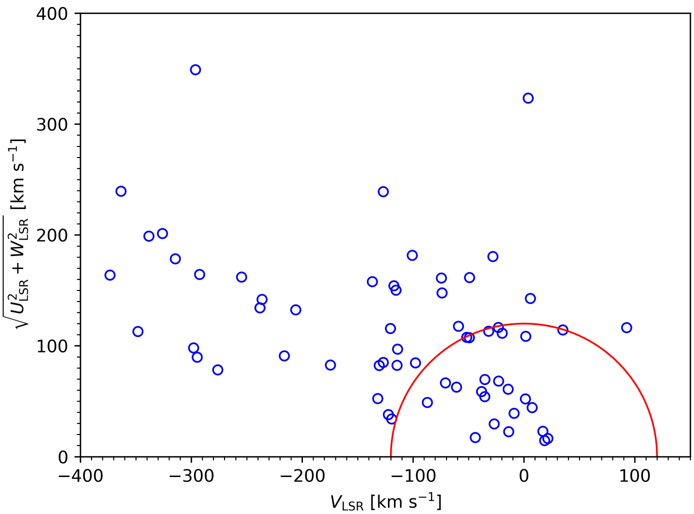

Figure 2: Toomre diagram showing the stars from our sample. Semicircle represent $|V_{LSR}|$ less than 120 km s^{-1}.

The Toomre diagram is a straightforward estimate of stars belonging to the Milky Way subsystems. The scatter of stars seen here in V_{LSR} indicates that no clear separation of disc stars is present, which is in favour of the previously used method. Disc stars are expected to be within the red semicircle, which is explained in detail in Stojanović (2015).

The reconstructed galactocentric orbits from our sample are shown in Fig. 3. The representative orbits from each population are shown in three rows: first row - typical thin disc stars; second row - thick disc stars and third row - halo stars. Each row shows two stars of the same population. For the thin and thick disc stars the orbits look quite similar. In the case of the two halo stars the orbits look different, because on the left the stars orbits symmetrically to the plane of the Galaxy, while on the right side the orbit is asymmetrical.

The case of the halo star (shown in Figure 3, third row on the right) may be due to the analytical potential used here since that star has a very high speed near the centre of the Milky Way.

From these results we can conclude that most of the Type II Cepheids in our sample 59.4% belong to the Halo. We plan to continue our investigation regarding the possible origins of these metal rich old stars.

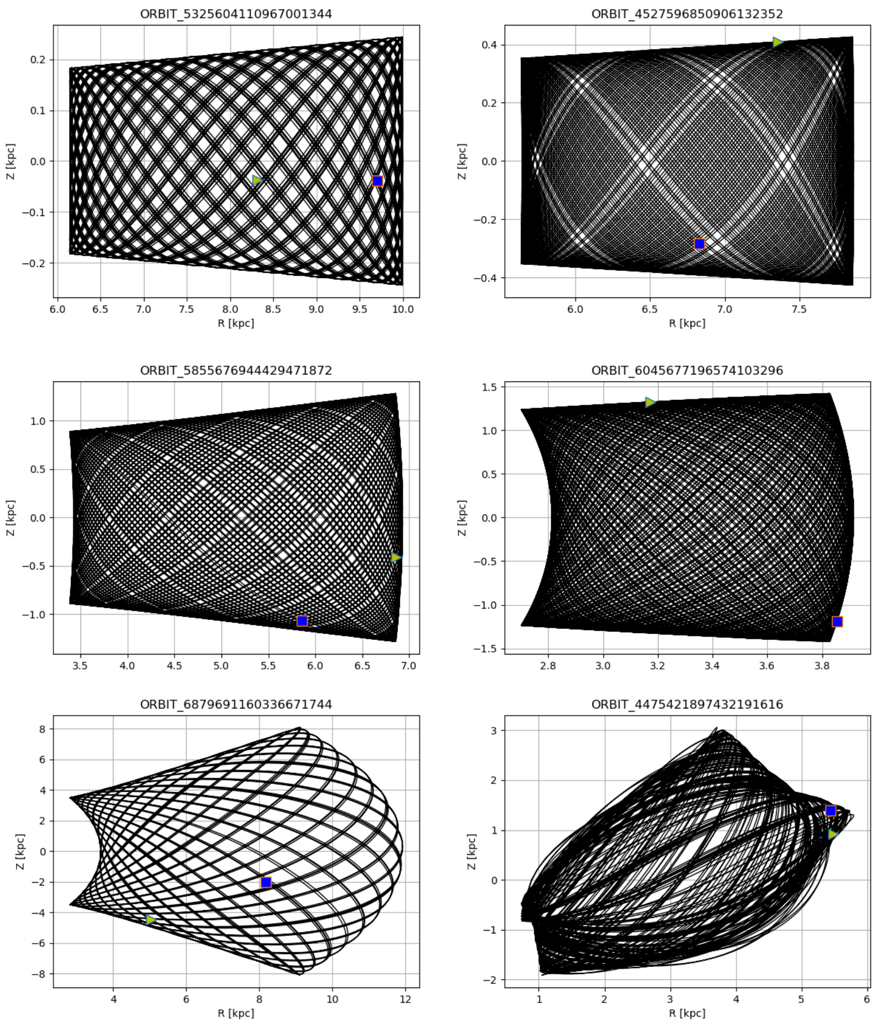

Figure 3: Examples of galactocentric orbits: first row - thin disc stars; second row - thick disc stars and third row - halo stars. Triangle symbol marks the starting point in integration, while the square is the last point in integration after 10 Gyr.

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