ORBITAL ANALYSIS OF OLD, HIGH LATITUDE CLUSTERS

Author: Àlex Drago González.
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Dra. Mercè Romero-Gómez
(Dated: June 18, 2020)

In early 2020, studies using *Gaia* DR2 provided us with information about all the visible clusters existent in the Milky Way. Two of them stood out for having high latitude, namely Berkeley 20 and Berkeley 29. The goal of this study is to shed some light into the clusters origin using orbital analysis. The results indicate that these old, high latitude clusters have almost circular orbits around the Galactic centre which seem to confirm the disc origin. We also conclude that Berkeley 20 value of Z is purely coincidental, given its uniform distribution across all ranges of latitude. Berkeley 29 positive value of Z suggests that the line-of-nodes of the Galactic plane does not correspond to the one imposed in the warped models, given its distribution on the XY projection.

I. INTRODUCTION

Before Gaia (ESA) took the challenge of creating an extremely precise map of the Galaxy, we did not have much evidence about the farthest clusters and stars that form the Milky Way. During fourteen months, Gaia gathered astrometric (positions) and photometric (mean G_{B_p} and G_{R_p} magnitudes) data from 1.14 billion sources and in 2016 Gaia revolutionised modern astronomy with the publication of precise information of the well-known open clusters in the first Gaia Data Release [1]. Later, Gaia DR2 [2] provided precise astrometric (positions, parallaxes and proper motions) and photometric (mean G, Bp and Rp magnitudes) data for 1.3 billion sources. This invaluable and unprecedented amount of information has led to the precise characterisation of well-known open clusters and the discovery of new ones. Recently, and using Gaia DR2 information, [3] provided us with a collection of the mean parameters of the 1481 clusters identified in the Milky Way together with an updated membership. Some of these parameters are useful to make a kinematic study of stellar clusters. We noticed that two clusters stand out for their high latitude. These clusters are Berkeley 20 and Berkeley 29 and these are the object of our study. Their singular position rise debates among the scientific community as some suggest they come from the halo while others defend that they are from the disc [3],[4]. Berkeley 29 is above the Galactic plane when it is in the down side of the warped disc, while Berkeley 20 is far below the disc than expected.

The goal of this work is to help disentangling the origin of the before mentioned clusters by making an orbital analysis. To do so, we used the catalogue of [5] and [6] that gather the mean positions, mean velocities and mean ages of 1481 open clusters, and Berkeley 20 and Berkeley 29 among them. This is the right time to perform such study because with Gaia DR2 astrometric data together with spectroscopic on-ground surveys, we can gather the 6D information of an open cluster for the first time with enough accuracy to perform an orbital analysis.

II. DATA SELECTION

The first step of this project was to make a clear distinction between the clusters we wanted to include. The two outer-disc ones are Berkeley 20 and Berkeley 29, which have values of Z of -4.301 kpc and 2.672 kpc respectively. To be able to compare the orbital analysis result of these two open clusters with the one of a typical thin disc cluster, we choose IC2391 as an open cluster in the Solar Neighbourhood with well-studied and expected disc properties.

From this data we extracted plots for the XY and YZ plane and we located those clusters (see Fig. 1).

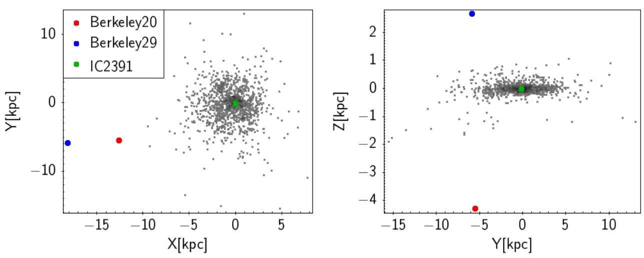

FIG. 1: XY (left) and YZ (right) projection of the total sample of open clusters. We highlight the open clusters selected for this study: Berkeley 20 (Red), Berkeley 29 (Blue) and IC2391 (Green).

III. DISC GALACTIC MODELS

We use three different Galactic models [7] to compute the clusters orbits. The Flat Model (F) describes the Galactic disc as a flat disc using the traditional Miyamoto-Nagai disc [8]. The results of this model are low-Z flat discs. The Symmetric Warped Model (S) tilts the orbit with an angle that only depends on the radius (R). The result is a disc with Z increasing with galactocentric radius R following a power law (see Eq. 1), where one side of the disc goes up and the opposite goes down symmetrically with an S-shape. The Lopsided Warped Model (L) also tilts the orbit, but its angle depends on the radius (R) and the galactocentric azimuth (θ). Again, the result is a bent disc with a typical S shape but with different amplitudes from the up and down side. We can describe the model using the tilt angle $\psi_M(R,\theta) = f(R)\psi(\theta)$, where $f(R)$, the power law function, is:

$$f(R) = \begin{cases} 0, & R \le R_1 \\ (\frac{R-R_1}{R_2-R_1})^{\alpha}, & R_1 < R < R_2 \\ 1, & R \ge R_2 \end{cases} \quad (1)$$

where R_1 and R_2 are the initial and final warp radius and $\alpha = 1.2$. In addition, $\psi(\theta)$ is:

$$\psi(\theta) = \begin{cases} 0, & \text{if } F \\ \psi_2, & \text{if } S \\ (A + Bsin(\theta)), & \text{if } L \end{cases} \quad (2)$$

where ψ_2 is a constant value that represents the amplitude of the warp at $R = 14$ kpc, $A = \frac{\psi_{up}+\psi_{down}}{2}$ and $B = \frac{\psi_{up}-\psi_{down}}{2}$, with ψ_{up} and ψ_{down} as the maximum amplitudes of the warp at the up and low side, respectively. We give values of $\psi_2 = 7.5$ deg for the symmetric warp and $\psi_{up} = 7.5$ deg and $\psi_{down} = 4.25$ deg for the lopsided warp.

IV. METHODOLOGY

We first compute the mean input parameters and, then, the orbit calculation.

A. Data processing

Cantat-Gaudin & Anders [3] provide the mean astrometric and spectroscopic values for the analysed open clusters. We downloaded the data from the Vizier site [15]. The mean values corresponding to Berkeley 20, Berkeley 29 and IC2391 are given in Table I, where we also include the $Log(age)$ in the last column and it will be used as the integration time (see next section).

In order to perform orbital analysis, we need to transform the equatorial heliocentric coordinates to Cartesian galactocentric coordinates, as in the Galactic models seen in the previous section. To perform such transformation, we use a Fortran code [16] that allows coordinate transformations for both positions and velocities. Thus, after applying the corresponding transformations, we obtain the mean positions and velocities: (X, Y, Z, Vx, Vy, Vz) for each cluster. The positions are given in kpc and velocities in km s^{-1}. The adopted value for the Solar radius from the Galactic centre is $R_{sun} = 8.43$ kpc and the circular velocity at the Solar radius of $V_c(R_{sun}) = 240$ km/s [9]. The peculiar motion of the Sun with respect to the local standard of res is $(U, V, W) = (11.1, 12.24, 7.25)$ km/s [10]. We repeat this process for the three clusters.

Cl.	$\bar{\alpha}$ [deg]	$\bar{\delta}$ [deg]	d_{mode} [kpc]	$\bar{\mu_\alpha}$ [mas/yr]	$\bar{\mu_\delta}$ [mas/yr]	$\bar{V_R}$ [km×s^{-1}]	age [log]
B20	83.2	0.19	14.44	0.81	-0.24	79.5	9.73
B29	103.3	16.9	19.24	0.15	-1.01	24.8	9.48
IC2391	130.3	-53.0	0.15	-24,64	23.32	14.54	7.47

TABLE I: Mean input variables in heliocentric equatorial coordinates for each of the open clusters for the orbit calculation.

B. Orbit calculation

In this section we perform the orbit integration for each of the open clusters, namely Berkeley 20, Berkeley 29 and IC2931. We use as initial conditions the mean values of each cluster in Cartesian galactocentric coordinates. We use a Runge-Kutta of order 7-8 with variable time-step to perform the orbit integration. For Berkeley 20 and Berkeley 29 we integrate backwards in time until the age of the cluster. As for IC2391, it is a young cluster of 48.5 Myr, thus it has performed less than 1/4 of a revolution. To be able to compare with Berkeley 20 and Berkeley 29, we integrate backwards 1 Gyr, and we highlight in different colour the actual age of 48.5 Myr. In Figs. 2, 3 and 4 we show the XY and YZ projections of each of the open clusters orbits.

Additionally, for each open cluster orbit, we write a Fortran code, that computes the orbital parameters, namely maximum, minimum and mean values for the galactocentric radius, R, and altitude with respect to the galactic plane, Z. We also compute the eccentricity defined as $e = (R_{max} - R_{min})/(R_{max} + R_{min})$. The results for each open cluster are given in Table II.

Cluster	M	Z_{max}	Z_{min}	Z_{mean}	R_{max}	R_{min}	R_{mean}	e
B20	F	5.05	-5.03	-0.11	21.99	13.99	17.90	0.22
	S	8.16	-7.38	-0.12	22.18	13.46	17.57	0.24
	L	6.24	-7.51	-0.11	22.27	13.55	17.73	0.24
B29	F	3.09	-3.37	-0.07	28.17	11.22	18.99	0.43
	S	10.99	-15.17	0.45	26.99	10.67	18.43	0.43
	L	9.84	-13.46	0.52	26.56	11.31	18.59	0.40
IC2391	F	0.00	-0.00	-0.00	8.60	7.75	8.19	5.19E-2
	S	0.08	-0.09	-0.00	8.60	7.76	8.17	5.10E-2
	L	0.14	-0.12	0.00	8.59	7.77	8.17	5.02E-2

TABLE II: Orbital parameters for each of the open clusters, Berkeley 20, Berkeley 29 and IC2391, specified in columns 3 to 9. In column 2, M shows with which Galactic model we obtain the orbital parameters: F for Flat model, S for Symmetric warp model and L for Lopsided warp model.

V. RESULTS AND ANALYSIS

In this section we analyse the orbits of each cluster.

A. IC2391

We use IC2391 as a test cluster with a well-known disc origin. It is currently located in the immediate Solar neighbourhood at heliocentric coordinates of $(X, Y, Z) = (0.001, -0.15, -0.018)$ kpc. In Fig. 2 we show the XY projection (left panel) and the YZ projection (right panel) using the Flat model. We only include the results for one model because the at present position of the cluster has a Galactocentric radius $R < R_1$, where R_1 is the initial radius of the warp. In this case, the three models coincide with the Flat model. We show the orbit that described the cluster during its lifespan in black and, with red colour, a simulated trajectory of 1 Gyr that lets us show several disc revolutions, as mentioned in Sect. IV B.

As expected, IC2391 has an almost circular orbit around the Galactic centre with a small excursion above and below the Galactic plane, of the order of few parsecs. In the following sections, we analyse the peculiar clusters Berkeley 20 and Berkeley 29 and we use IC2391 as a reference.

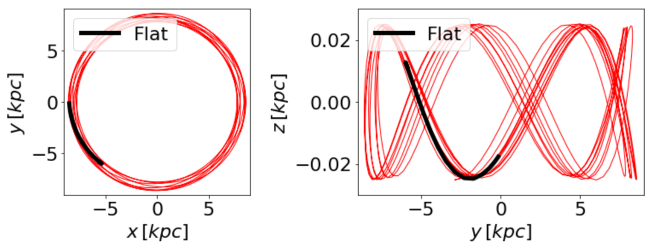

FIG. 2: Flat model for **IC2391**, *Left*: XY projection. *Right*: YZ projection. In red the orbit during 1 Gyr. In black, is shown the orbit from the present time to its birth.

B. Berkeley 20

In Fig. 3 we show the XY (top panels) and YZ (bottom panels) projections of the orbit followed by Berkeley 20 computed using the three Galactic models described in Sect. III, namely the Flat model (F), the Symmetric warp model (S) and the Lopsided warp model (L) (left, middle and right panels, respectively). The XY projection is colour-coded by the distance Z to the Galactic plane and the black dot marks the present position, while the YZ projection is colour-coded by the backwards integration time, being zero the present time. We currently find the cluster in the heliocentric Cartesian coordinates $(X, Y, Z) = (-12.6, -5.5, -4.3)$ kpc.

For the Flat model (F), we see that the coordinate Z lies between -5 kpc and 5 kpc and has a mean value of $Z_{mean} = -0.11$, almost null. We also notice that the radius has a notable variation between the minimum and maximum values, which results on a non-zero eccentricity, with a value of $e = 0.22$. In addition, we found that the mean value of the radius, $R_{mean} = 17.9$ kpc, matches with the data given in the DR2 [2]. For the Symmetric Warp model (S), we show the XY projection is similar to the Flat model and the values of R and e match the previous model. However, the YZ projection show an inclination of the orbits that results in an increase of the extreme values of Z, with a $Z_{min} = -7.38$ kpc and $Z_{max} = 8.16$ kpc. Despite we reach the same value of Z_{mean} as before, now the altitude range is larger. For the Lopsided Warp model (L), we see that the XY projection and values of the radius and the eccentricity still have similar values as before. Now though, we can appreciate that the YZ projection is not lineal, but has different declination in each side of the orbit. This results in a bigger absolute value of Z_{min} than Z_{mas}, despite it still has a $Z_{mean} = -0.12$ kpc.

The analysis of the distance to the Galactic plane for each of the disc models leads to the following conclusions: As for the Flat model, the behaviour is an expected vertical oscillation with Z_{mean} almost null. When using the warped models, either symmetric or lopsided, we obtain that, in mean, the open cluster trajectory lies at the up or down side of the Galactic plane imposed by the model. The crossings to the Galactic plane do not always happen when crossing the imposed line-of-nodes (the x-axis). This could suggest that the line-of-nodes of the Galactic plane does not correspond to the one imposed in the model.

In the temporal analysis of the bottom panel, we verified the trajectory is evenly distributed without favouring any position in the space, which suggests that the current high value of altitude is just a coincidence.

C. Berkeley 29

Analogously, in Fig. 4 we show the XY (top panels) and YZ (bottom panels) projections of the orbit followed by Berkeley 29 computed using the three Galactic models described in Sect. III, namely the Flat model (F), the Symmetric warp model (S) and the Lopsided warp model (L) (left, middle and right panels, respectively). The XY projection is colour-coded by the distance Z to the Galactic plane and the black dot marks the present position, while the YZ projection is colour-coded by the backwards integration time, being zero the present time. We currently find the cluster in the heliocentric coordinates $(X, Y, Z) = (-18.1, -5.9, 2.7)$ kpc.

The first row of plots correspond to the Flat model (F) adjustment. The XY projection shows that the cluster has a greater variation in its radius than the case of Berkeley 20. Now, the R_{min} is significantly different than R_{max}, which results in a grater eccentricity, with a value of $e = 0.43$. Also, the mean value of the radius is $R_{mean} = 19.0$ and matches the data given in DR2 [2]. Moreover, Z_{min} is similar to Z_{max} and the mean value of the latitude is almost zero. For the Symmetric Warp model (S), the XY projection and the values of

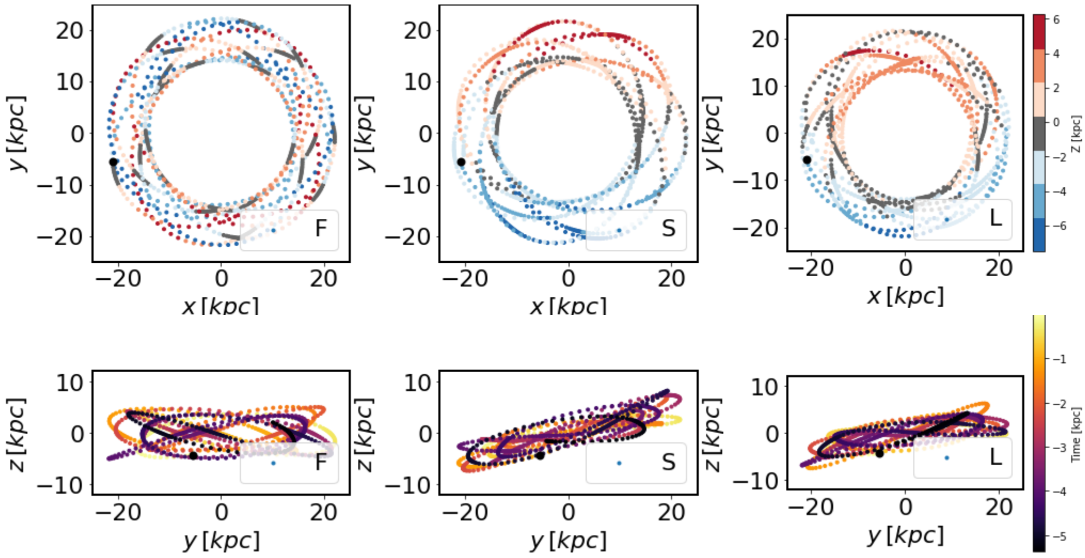

FIG. 3: For **Berkeley 20**, *Top*: XY projection which is colour-coded by the distance Z to the Galactic plane. *Bottom*: YZ projection which is colour-coded by the backwards integration time from its birth to the present moment. *Left*: Flat model. *Middle*: Symmetric warp model. *Right*: Lopsided warp model. The black dot indicate the current position of the cluster.

R and e are similar to the previous model. Regarding latitude, we observe that $Z_{min} = -15,2$ kpc, which has a greater absolute value than $Z_{max} = 11.0$ kpc. This may lead us to think that Berkeley 29 spends most of its lifespan with negative latitude, but the positive value of $Z_{mean} = 0.5$ kpc suggests the opposite. For the Lopsided Warp model (S), we have similar values of the radius and the eccentricity as before. We also notice that Z_{min} is very negative and $|Z_{min}| >> |Z_{max}|$, but with a lesser extent than before. Now, $Z_{mean} = 0.52$ kpc that suggest a slight tendency of Berkeley 29 to be in the upper plane of latitude.

In this case, the analysis of the distance from the Galactic plane indicates a similar pattern to that of the cluster Berkeley 20. The particularity of Berkeley 29 is that, at the present time, it is located above the Galactic plane, when it should be slightly below it. From the trajectory using the warped models, either symmetric or lopsided, we see that at birth it was located above the Galactic plane, as we would expect, and at the last revolution around the Galactic centre the trajectory tilts upwards. We note that the crossings to the Galactic plane do not occur either when crossing the imposed line-of-nodes (x-axis), and as we suggest for Berkeley 20, the real line-of-nodes might not coincide with the imposed in the model.

In the temporal analysis of the bottom panel, we see that in the early stage of the cluster it seems like it had a flat behaviour and deviated over time with the warp models. We also notice that the used model changes the birth position of the cluster, being $(X, Y, Z)_F = (-25.2, -7.6, -2.6)$ kpc, $(X, Y, Z)_S = (-27.2, 4.3, 3.9)$ kpc and $(X, Y, Z)_L = (-27.1, 1.7, 4.5)$ kpc. We expect differences between the different models, but the detailed analysis of them is not the aim of this project.

VI. CONCLUSIONS

In this work, we wanted to contribute to the debate on whether Berkeley 20 and Berkeley 29 belong to the disc or they have a halo origin. With our study, we show that the models match the kinetic behaviour of the two clusters so we favour the disc origin.

We also saw that the current low latitude of Berkeley 20 is purely coincidental because it is evenly distributed over time through the orbit. We noticed that despite it may look like Berkeley 29 spent most of its life in negative values of Z, it actually has a positive Z_{mean}, which suggests the cluster had a tendency of being above the Galaxy plane.

Finally, from the analysis of the distance of the cluster from the Galactic plane, the orbital analysis suggest that the real line-of-nodes may not coincide with the imposed in the warped models (x-axis). This possibility is in agreement with the results found in the literature based on Cepheids [12] and [13] and based on *Gaia*DR2 young OB and RGB populations [7] and [14].

Acknowledgments

I would like to express my gratitude to my tutor and advisor Dr. Mercè Romero for the help given and the time she invested in this project. I would also like to thank Dr. Tristan Cantat-Gaudin for kindly providing the ages of the open clusters before being published. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.`

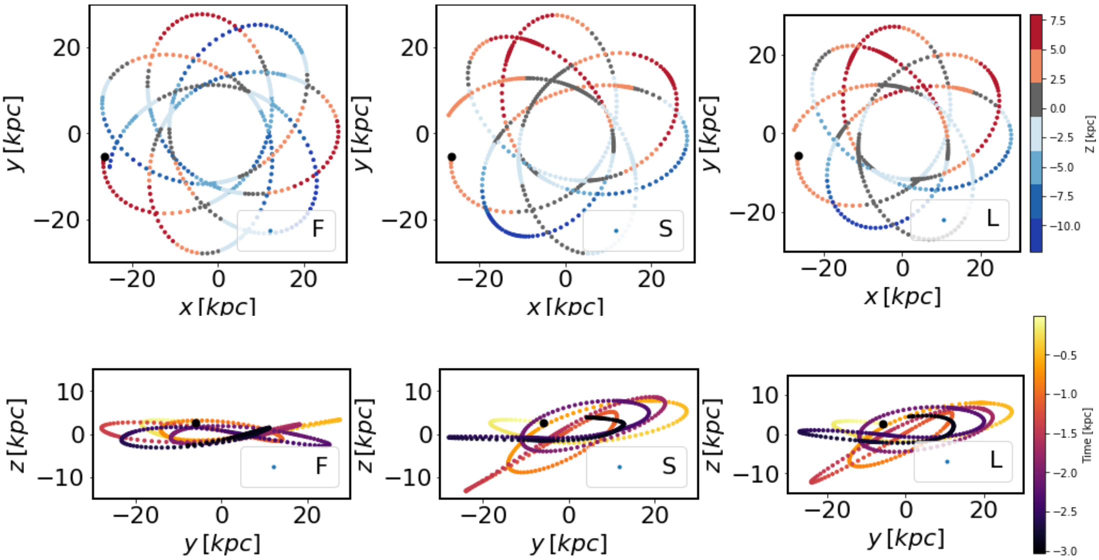

FIG. 4: As in Fig. 3 for **Berkeley 29**.

`esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. I would also like to thank my friends and family for their unconditional support.

[1] van Leeuwen, F. et al. (Gaia Collaboration). "Gaia Data Release 1. Open cluster astrometry: performance, limitations, and future prospects". Astronomy & Astrophysics **601** : 65-86 (2017)
[2] Brown, A. G. A. et al. (Gaia Collaboration) "Gaia Data Release 2. Summary of the contents and survey properties". Astronomy & Astrophysics **616** : 22-43 (2018)
[3] Cantat-Gaudin, T.; Anders, F.; Castro-Ginard, A.; Jordi, C.; Romero-Gomez, M. et al. "Painting a portrait of the Galactic disc with its stellar clusters". arXiv.org/pdf/2004.07274
[4] Cantat-Gaudin, T.; Donati, P.; Vallenari, A.; Sordo, R.; Bragaglia, A.; Magrini, L. "Abundances and kinematics for ten anticentre open clusters". Astronomy & Astrophysics. **588** : 120-137 (2016)
[5] Cantat-Gaudin, T.; Krone-Martins, A.; Sedaghat, N. et al. "Gaia DR2 unravels incompleteness of nearby cluster population: new open clusters in the direction of Perseus" Astronomy & Astrophysics **624** : 126-143 (2019)
[6] Castro-Ginard, A.; Jordi, C.; Luri, X.; Julbe, F.; Morvan, M.; Balaguer-Nuñez, L.; Cantat-Gaudin, T. "A new method for unveiling open clusters in Gaia. New nearby open clusters confirmed by DR2". Astronomy & Astrophysics **618** : 59-77 (2018).
[7] Romero-Gómez, M.; Mateu, C.; Aguilar, L.; Figueras, F.; Castro-Ginard, A. "Gaia kinematics reveal a complex lopsided and twisted Galactic disc warp". Astronomy & Astrophysics **627** : 21-35 (2019)
[8] Allen, Christine; Santillan, Alfredo "An improved model of the galactic mass distribution for orbit computations". Revista Mexicana de Astronomia y Astrofisica. **22** : 255-265 (1991)
[9] Reid, M. J., et al. "Trigonometric Parallaxes of High Mass Star Forming Regions: The Structure and Kinematics of the Milky Way". The Astrophysical Journal **783**: 130-144 (2014)
[10] Schönrich, R.; Binney, J.; Dehnen, W. "Local kinematics and the local standard of rest". Monthly Notices of the Royal Astronomical Society **403**: 1829-1833 (2010)
[11] E. B. Amores, A. C. Robin, C. Reyle. "Evolution over time of the Milky Way's disc shape". Astronomy & Astrophysics **602** : 67-86 (2017)
[12] Skowron, D. M., et al. "A three-dimensional map of the Milky Way using classical Cepheid variable stars". Science **365**: 478-484 (2019)
[13] Skowron, D. M., et al. "Mapping the Northern Galactic Disk Warp with Classical Cepheids". Acta Astronomica **69**: 305-320 (2019)
[14] Poggio, E., et al. "Evidence of a dynamically evolving Galactic warp". Nature Astronomy **4**: 590-596 (2020)
[15] https://vizier.u-strasbg.fr/viz-bin/VizieR-2
[16] Available at https://github.com/mromerog