Kinematics analysis of the transient Milky Way warp using RGB stars from Gaia DR2

R M Nurhidayat, M I Arifyanto and H R T Wulandari
Astronomy Research Division, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Indonesia
E-mail: rizman.nana@students.itb.ac.id

Abstract. The perturbations to the Milky Way cause the disk to have bending or breathing wave, flare, and warp. Both spatial analyses from stellar and gas show the Milky Way warp can be approached with sinusoidal function to the Galactocentric longitude. In this research, we aim to find evidence of the transient Milky Way warp using kinematics data of the Red Giant Branch (RGB) stars from Gaia Data Release 2. We only use RGB stars with positive parallaxes and small parallax uncertainties where $\varpi > 0$ and $\varpi/\sigma_{\varpi} > 5$, respectively. Using the linear warp model, we find the Milky Way warp starts on $R_w = 10.72$ kpc, with the amplitude ($\gamma_w$) of 0.39 and the Line of Node lies on $\phi_w = -5.26^\circ$. Assumed the warp is a static long-lived feature on kinematics distribution, where all of the warp parameters are constant by the time, the observed vertical velocity ($V_z$) is less than the expected one. The maximum $V_z$ is not exceeded to 12.5 km/s rather 20 km/s derived from the proposed model. It infers that the warp drive on the Milky Way is a transient feature. One of the possible reasons is the recent interaction with satellite galaxies in perturbing the outer disk of the Milky Way.

1. Introduction
Warped galactic disk is not a special feature that could be found in spiral galaxies. From 325 edge-on spiral galaxies, 236 galaxies are driving warped disks [1]. Our galaxy, Milky Way also presents a warped feature, among gas, dust, and stars components. The warp parameters, the starting radius in which the disc starts to deviate, the warp amplitude, and line-of-node (LoN) are different, based on the tracers [2, 3, 4].

HI maps reveal the majority of gas lies on galactic longitude $l < 180^\circ$ are above the galactic plane or towards to North Galactic Pole (NGP) and on $l > 180^\circ$ are dominated by the gas that bends to the South Galactic Pole (SGP) [2]. The young and old population stars, OB and Red Giant Branch (RGB) are also deviating to the galactic plane [3]. It has a similar pattern with the warped gas but with a higher maximum warp amplitude. The starting warp radius ($R_w$) on RGB stars is estimated at 10.5 – 11 kpc. OB stars show so complicated warp pattern that $R_w$ is hiding on 12 – 13 kpc.

Kinematics analysis can predict where $R_w$ starts to bend the disk. As the disk drives no warp structure, the vertical velocity ($V_z$) tends to 0 km/s. Data show $V_z$ is increasing as a function of Galactocentric radius $R$ [5]. The Upper Main-Sequence (UMS) stars show the warp signature at $R > 12$ kpc and RGB stars present the significance of increasing $V_z$ at $R > 10$ kpc.

This research aims to find the evidence of the transient warp in the Milky Way by applying the static warp model in kinematics distribution and assuming the disc is an unrelaxed structure
in radial axis, using RGB stars from Gaia Data Release 2 (DR2) [6, 7].

2. Data and Methods
We obtain RGB stars from Gaia DR2 by selecting stars with positive parallax \( \varpi > 0 \) and \( \varpi/\sigma_\varpi > 5 \) to achieve better distance approximation [8]. Then, selecting stars that have absolute magnitude \( M_G < 3 \) and intrinsic color \( (G_{BP} - G_{RP})_0 > 0.95 \) [9] using equation (1) and equation (2).

\[
M_G = G + 5 \log \varpi + 5 - A_G < 3 \tag{1}
\]

\[
(G_{BP} - G_{RP})_0 = (G_{BP} - G_{RP}) - E(G_{BP} - G_{RP}) > 0.95, \tag{2}
\]

with \( G, G_{BP}, \) and \( G_{RP} \) are the magnitudes in G-band (330 – 1050 nm), magnitude at 330 – 680 nm, and 630 – 1080 nm, respectively. \( A_G \) represents the extinction in G-band and \( E(G_{BP} - G_{RP}) \) is the color excess. We remove all RGB candidates with no radial velocity parameter. After applying it, we get 2,674,064 stars.

We use a linear warp function [4] to perform an approximation of the observed data, as shown in equation (3).

\[
Z = \gamma(R - R_w) \sin(\phi - \phi_w) \tag{3}
\]

\( Z \) is the vertical position relatives to the galactic plane in galactocentric coordinates, where \( Z > 0 \) is going to the direction of NGP and \( Z < 0 \) towards SGP. When \( R < R_w \), the disk is assumed to be unwarped and for \( R > R_w \) the disk starts to warp in a function of \( R \) and Galactocentric longitude \( \phi \). We take the initial \( \phi \) is starting from Galactic Center-Sun (GC) line, rotating with a similar direction of the galactic rotation. The line-of-node, \( \phi_w \), lies on the GC line if \( \phi_w = 0^\circ \). \( \gamma \) is the amplitude of the warp.

To get all warp parameters on equation (3), we use the combination of logistic function and No U-turn Sampler (NUTS) algorithm. In the first step, we use the logistic function to separate the unwarped data and the warped data by determining \( R_w \) alongside running NUTS to achieve the other parameters on each group. Then, we select the warped data with \( R > R_w \) and apply NUTS algorithm to get \( \gamma \) and \( \phi_w \).

In finding the transience of the warp, we use the kinematic warp model by deriving \( Z \) from equation (3) over time, as shown in equation (4) with \( V_\phi \) is the rotational velocity. We assume that warp in Milky Way is static in which \( \gamma, R_w, \) and \( \phi_w \) are constant over time and the disk is not relaxed radially \( dR/dt = 0 \).

\[
V_z = \frac{V_\phi}{R} \gamma(R - R_w) \cos(\phi - \phi_w) \tag{4}
\]

We compare the vertical velocity \( V_z \) from equation (4) and the observed vertical velocity \( V'_z \) from the data using equation (5).

\[
V'_z = V_r \sin(b) + V_b \cos(b) + V_{z,\odot} \tag{5}
\]

with \( V_r \) is the radial velocity of each star, \( b \) is the galactic longitude, \( V_b \) shows the velocity on \( b \) axis, and \( V_{z,\odot} \) is the solar motion in the Z-axis. We adopt \( V_{z,\odot} = 7.25 \) km/s [10].

3. Result and Analysis
We present the number density of our RGB stars in logscale, shown in figure 1. It shows the exponential decreasing function in radial and vertical axis and reveals the extinction effect by the interstellar medium in the line-of-sight direction called Finger of God feature. To analyze
the warp pattern, we perform binning methods on X and Y coordinates and calculate the mean of Z for each bin, as shown in figure 2.

The two-dimensional projections of mean Z in figure 2 show two different areas of red-coded and blue-coded color. The areas are representing the Southern Warp and Northern Warp with the boundary is around negative $\phi$. Its boundary could be the LoN of the warp, which will be determined by applying the logistic function and NUTS algorithm.

We apply further selection before finding the warp parameters. We get 2,296,373 RGB stars after selecting RGB stars with $6 < R < 15$ kpc and $-30^\circ < \phi < 30^\circ$. To visualize the warp pattern, we only select a bin that contains more than 100 stars after performing binning methods in Z as a function of R and $\phi$ with the size of the bins are 0.25 kpc in R and 10$^\circ$ for $\phi$, as shown in figure 3. The maximum deviation in Southern Warp reaches $-0.8$ kpc and it is about 0.6 kpc in Northern Warp. It drives us to expect that the LoN is not lying on $\phi = 0^\circ$.

The warp parameters in equation (3) are determined by applying the logistic function and NUTS algorithm in PyMC3, an MCMC python library. The posterior distribution for $\gamma$, $R_w$, and $\phi_w$ is shown in figure 4. The median of starting radius of the warp $R_w$ is 10.72 kpc, LoN lies on $\phi_w = -5.24^\circ$ with the warp amplitude $\gamma$ of 0.39. The results are in-line with some researches.
that estimate $R_w$ around 10 kpc [3, 5] and LoN is on negative $\phi$ [3], in the coordinates we used. The calculation of median $V'_z$ in XY projection is shown in figure 5. The significance of increasing $V'_z$ is on about 10 kpc, coinciding with the $R_w$ as predicted in the warp model that drives both spatial and kinematics distribution [5].

To compare $V_z$ and $V'_z$, we substitute the posterior distribution to equation (4) to get $V_z$ and calculate $V'_z$ of each RGB star in the selected areas of $R$ and $\phi$. We present the mean of $V'_z$ in binned $R$ and $\phi$ with the size of 0.25 kpc and 10°, respectively, as shown in figure 6. The maximum $V'_z$ is not more than 12.5 km/s, less than the vertical velocity in the static warp model we get from equation (4) that can reach 20 km/s. This result leads us to expect that the Milky Way is not a static feature, but rather a transient one. The warp is also a long-lived structure because we can observe it in RGB stars, one of the old population stars.
Based on the galaxy formation simulation, there are at least four mechanisms that drive warp structure in a galaxy [11]. They are (1) tidal interaction with satellite galaxy in close encounter phase, (2) the interaction with a massive satellite galaxy on distant fly-bys phase, (3) misalignment of cold accretion gas, and (4) re-accretion of cold gas from gas-rich progenitors in a major merger case. The transience of the warp can be related to the dynamics of the Milky Way. Recent researches [3, 4, 5] suggest that the warp is driven by the interaction between Milky Way and its satellite galaxy. One of the most probable suspects is the Sagittarius dwarf galaxy that orbits Milky Way in polar orbit.

The transient warp can be considered as the effect of a dynamical motion from the warp itself. It rotates around the vertical axis of the inner disk while the orientation of the disk is fixed. This model expects the warp is coming from the interaction of a satellite galaxy. The second one is the entire galactic disk is precessing about the normal axis of the inner disk.

4. Conclusion
The warp pattern shown in our RGB stars reveals the shifted LoN on $\phi_w = -5.24^\circ$ with the amplitude $\gamma$ of 0.39. The starting radius of the warp $R_w$ from the spatial analysis is 10.72 kpc, coinciding with the expected $R_w$ from kinematics distribution. The observed vertical velocity $V_z^\prime$ is weaker than the predicted vertical velocity $V_z$ derived from the static warp model. It
indicates that the warp in Milky Way is a transient structure. This transience may come from the interaction with the satellite galaxy or the precession motion of the entire disc towards its normal axis. Further analysis needs to be performed by building the dynamics model of our galaxy, the Milky Way.

Acknowledgments
The authors appreciatively acknowledge the Program of Research, Community Service, and Innovation of the Institut Teknologi Bandung (P2MI ITB) to give us a grant for this work. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.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.

References
[1] Ann H B and Park J-C 2006 New Astron. 11 293
[2] Levine E S, Blitz L and Heiles C 2006 ApJ 643 881
[3] Romero-Gómez M, Mateu C, Aguilar L, Figueras F and Castro-Ginard A 2019 A&A 627 A150
[4] Chen X, Wang S, Deng L, de Grijs R, Liu C and Tian H 2019 Nature Astronomy 3 320
[5] Poggio E, Drimmel R, Lattanzi M G, Smart R L, Spagna A, et al. 2018 MNRAS 481 L21
[6] Gaia Collaboration, Prusti T, De Bruijne J H J, Brown A G A, et al. 2016 A&A 595 A1
[7] Gaia Collaboration, Brown A G A, Vallenari A, Prusti T, et al. 2018a A&A 616 A1
[8] Bailer-Jones C A L 2015 PASP 127 994
[9] Gaia Collaboration, Katz D, Antoja T, Romero-Gómez M, et al. 2018b A&A 616 A11
[10] Schönrich R, Binney J and Dehnen W 2010 MNRAS 403, 1829
[11] Gómez F A, White S D M, Grand R J J, Marinacci F, Springel V and Pakmor R 2017 MNRAS 465 3446