Galactic Dynamics in the Era of Large Surveys
Proceedings IAU Symposium No. 353, 2019
M. Valluri & J. A. Sellwood, eds.

doi:10.1017/S174392131900869X

A 3D map of the Milky Way's disk as traced by classical Cepheids

Xiaodian Chen[1], **Shu Wang**[1], **Licai Deng**[1,2], **Richard de Grijs**[3,4,5], **Chao Liu**[1] and **Hao Tian**[1]

[1]Key Laboratory for Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China
email: chenxiaodian@nao.cas.cn

[2]Department of Astronomy, China West Normal University, Nanchong 637009, China

[3]Department of Physics and Astronomy, Macquarie University, Balaclava Road, Sydney, NSW 2109, Australia

[4]Research Centre for Astronomy, Astrophysics and Astrophotonics, Macquarie University, Balaclava Road, Sydney, NSW 2109, Australia

[5]International Space Science Institute–Beijing, 1 Nanertiao, Zhongguancun, Hai Dian District, Beijing 100190, China

Abstract. We have collected 2330 Cepheids to establish an intuitive 3D map of the Milky Way's disk. As regards the warp amplitude, the Cepheid disk agrees well with the gas disk for radii up to 15 kpc. However, the mean line of nodes (LON) of the Cepheid disk deviates from the Galactic Center–Sun direction by $17.5 \pm 1.0^{\circ}$. This is a new and different result compared with previous results. The LON is not stable at any given radius, but it twists. The twisted pattern suggests that the formation of the Milky Way's warp is dominated by the massive inner disk. The kinematic warp defined by the Cepheids is also in concordance with the spatial warp. In the 2020 era, the anticipated increasing number of new Cepheids will provide a key opportunity to view our Milky Way's disk as a whole, and we expect that our knowledge of the disk's main structural features will be much improved.

Keywords. Galaxy: disk, Galaxy: structure, stars: variables: Cepheids, stars: distances

1. Introduction

Our Milky Way's disk is embedded in dust and gas, and heavy extinction prevents us from knowing the morphology of the disk in detail, especially that of the stellar disk. In the last decade, the stellar disk has been studied mainly based on Two Micron All Sky Survey (2MASS) data. Although the 2MASS near-infrared (near-IR) photometry can reduce the effects of extinction, its shallow limiting magnitude results in limited spatial coverage of the whole disk. *Gaia* Data Release (DR) 2 is an unprecedented catalog containing more than one billion stars with parallaxes and proper motions. This database facilitates studies of our Milky Way in 6D phase space. However, as we are limited by the parallax uncertainties, it is still difficult to study the inner and outer disk based on *Gaia* data alone.

Classical Cepheids are the brightest and most commonly used variable stars. They serve as primary distance indicates in establishing the cosmological distance ladder. The *Hubble Space Telescope* (HST) has facilitated discoveries of thousands of Cepheids in spiral galaxies during the last 20 years. Unlike extragalactic Cepheids, however, Cepheids in our Milky Way are not well-studied. Before 2018, only ∼1000 classical Cepheids located within 3 kpc of the Sun were known. As some time-domain surveys have shifted their

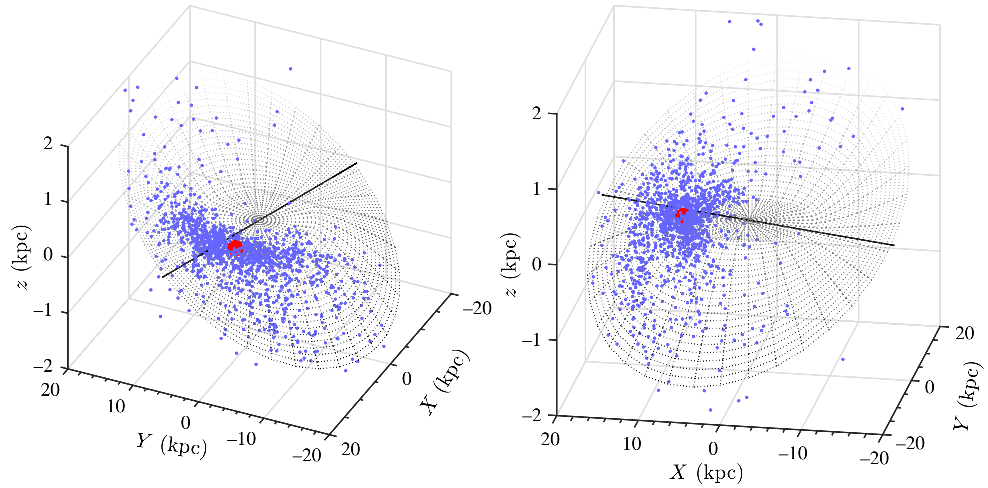

Figure 1. (left) 3D map of the Milky Way disk traced by 1485 classical Cepheids (blue dots). The red filled circle denotes the position of the sun and the grid is the best-fitting warp model (based on a power-law model). The mean line of nodes of the warp is shown as the solid black line. (right) As the left panel, but for a different view.

focus to the Galactic plane, this situation is now changing. The Wide-field Infrared Survey Explorer (WISE) Catalog of Periodic Variable Stars (Chen *et al.* 2018) contains 1312 new Cepheids for which mid-infrared WISE photometry is available. Optical surveys such as the All-Sky Automated Survey for Supernovae (ASAS-SN; Jayasinghe *et al.* 2018), the Asteroid Terrestrial-impact Last Alert System (ATLAS; Heinze *et al.* 2018) and *Gaia* DR 2 have also found several hundred new Cepheids (Ripepi *et al.* 2019). Based on this large collection of Cepheids, an accurate 3D map of the Milky Way can be constructed.

2. A 3D map of the Milky Way

Classical Cepheids are usually contaminated by Type II Cepheids and eclipsing binaries if the classiciation is done using light curves. Here, we adopted *Gaia* parallaxes to exclude these faint contaminators. We thus obtained a sample of 2330 classical Cepheids. We calculated the distances to these Cepheids using a combination of near-IR and mid-IR bands. The absolute magnitudes of Cepheids are determined by their near-IR and mid-IR period–luminosity relations (Chen *et al.* 2017; Wang *et al.* 2018). We adopted an $\alpha = 2.05$ IR extinction law (Chen *et al.* 2018) to correct for the effects of extinction. This law conforms with the recent Galactic extinction law determined based on the *Gaia* DR 2 database (Wang & Chen 2019).

We convert the three-dimensional (α, δ, d) coordinates to (X, Y, z) in Galactocentric coordinates. Figure 1 shows the distribution of these Cepheids, as well as the morphology of the young stellar disk (Chen *et al.* 2019). The most intuitive structure in the 3D map is the obvious warp in the outer disk. The warp turns upward on the left-hand side and downward on the right-hand side. This warp morphology was recently confirmed independently by Skowron *et al.* (2019) based on a slightly larger yet overlapping Cepheid sample predominantly drawn from the OGLE database.

To analyze the Milky Way's spatial warp, we adopted linear and power-law warp models to fit to the distribution of our Cepheids. We found that the Milky Way's warp can be well-described by a linear model beyond a Galactocentric radius of 9.4 kpc, while the power-law model is more suitable to avoid a discontinuity at the warp's onset radius. The best-fitting warp models are $z_w = 0.148 \times (R - 9.26) \cdot \sin(\phi - 17.4)$ (linear model)

https://doi.org/10.1017/S174392131900869X Published online by Cambridge University Press

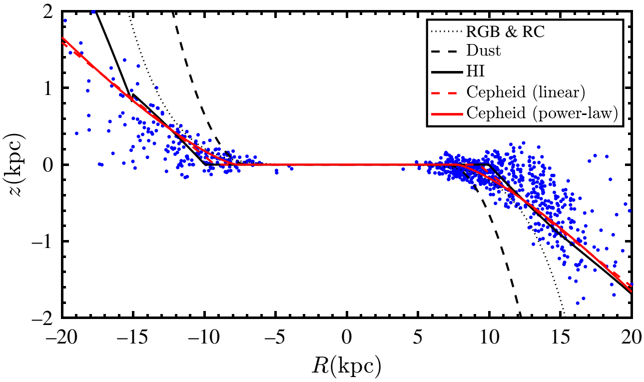

Figure 2. Comparison of different warp amplitudes. The red dashed and solid lines are the amplitudes of the Cepheid warp according to the linear and power-law models, respectively. The warps traced by gas, dust, and red giants are shown as black solid, dashed, and dotted lines, respectively.

and $z_w = 0.060 \times (R - 7.72) \cdot \sin(\phi - 17.5)$ (power-law model). We compared the warp's maximum amplitude to previous work, traced by either gas, dust, or red-giant stars (Levine *et al.* 2006; Drimmel & Spergel 2001; López-Corredoira *et al.* 2002), and found that the Cepheid warp agrees well with the gas warp within 15 kpc (see Figure 2). However, the difference with respect to the warp traced by old stars may be owing to evolution or completeness problems associated with the 2MASS data. Beyond 15 kpc, both the Cepheid and gas warps contain an $m = 2$ mode with an amplitude of $W_2 = 0.14$ kpc kpc^{-1}, but their phases ϕ_{W2} are different. The presence of an $m = 2$ mode means that the morphology of the warp in the outer regions is even more complicated.

3. The Warp's LON and Kinematics

As regards the angle of the line of nodes (LON), the Cepheid warp deviates from the Galactic Center–Sun direction by $\phi_{\rm w} = 17.5 \pm 1.0$. This angle is different from that reported previously, based on either gas, dust, or old stars. By checking the LON angle in each radial bin, we found that the LON is twisted. The warp onset appears at $R \sim 8$ kpc, and its LON decreases in the range of 9–12 kpc. Between 12 kpc and 15 kpc, the LON angle increases significantly, and we observe a twist around 15.5 kpc. This trend seen for the Milky Way warp's LON conforms to the theoretical predictions of Shen & Sellwood (2006). Their theory suggests that during the formation of the Milky Way's warp, the torque caused by the massive inner disk is more important than that caused by external material.

Gaia DR 2 also provides the proper motions for the majority of Cepheids and the mean radial velocities for a small sample of Cepheids. We can therefore also analyze the Cepheid disk kinematically. The proper motions and mean radial velocities of 782 Cepheids were converted to 3D velocities in the Galactocentric coordinates (v_r, v_ϕ, v_z). The distribution of v_ϕ agrees with a flat rotation curve, $v_r = 240$ km s^{-1} (see the left-hand panel of Figure 3). We adopted this flat rotation curve to determine the vertical velocities v_z of the other two-thirds of our Cepheid sample. The left-hand panel of Figure 3 shows the v_z distribution in the (X, Y) plane. Cepheids with large v_z are shown as red (positive velocity) and blue (negative velocity) dots. In the solar direction, the average v_z increases with Galactocentric radius. This is the warp's feature (see also Poggio *et al.* 2018; Romero-Gómez *et al.* 2019). The red dots denote the probable kinematic LON of

https://doi.org/10.1017/S174392131900869X Published online by Cambridge University Press

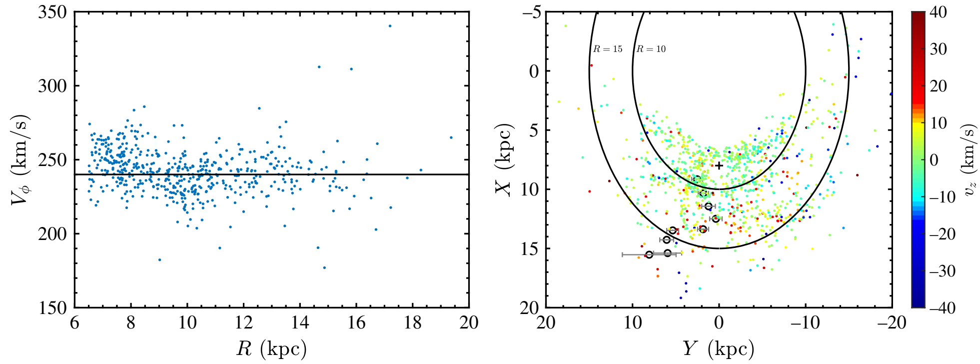

Figure 3. (left) Rotation speed of the Cepheids (blue dots) and a flat rotation curve (solid black line). (right) The colorful dots represent the v_z distribution in the XY plane. Cepheids with large and small v_z are shown in red and blue, respectively. The grey circles and error bars are the LON of the spatial warp. The two black circles represent $R = 10, 15$ kpc and the Sun's position is indicated by a black plus sign.

the warp. These LON values are obviously tilted and comparable to the spatial LON shown as grey circles if we take into account the uncertainties.

4. Conclusion

Based on a significantly enhanced sample of classical Cepheids, we established an intuitive and accurate 3D map of the Milky Way disk. The flare and warp in the outer disk are well-defined. As regards the amplitudes of the flare and the warp, the Cepheid disk agrees well with the gas disk within 15 kpc. Based on the Cepheid disk, we found that our Sun deviates from the warp's LON by 17.5°. More interestingly, the Milky Way's warp twists in both spatial structure and kinematics. This twisted pattern implies that the formation of the warp was dominated by the massive inner disk. In the 2020 era, the number of classical Cepheids will likely be more than doubled, and more Cepheids will have mean radial velocity information. These new Cepheids will cover the other side and the edge of our Milky Way with better completeness. Our knowledge of the Galactic rotation curve, the spiral arm structure, the flare, and the warp will be verified by the new view away from the Galactic Center–Sun direction made possible by these new data.

References

Chen, X., de Grijs, R., & Deng, L. 2017, *MNRAS*, 464, 1119
Chen, X., Wang, S., Deng, L., *et al.* 2018, *ApJ*, 859, 137
Chen, X., Wang, S., Deng, L., *et al.* 2018, *ApJS*, 237, 28
Chen, X., Wang, S., Deng, L., *et al.* 2019, *Nat. Astron.*, 3, 320
Drimmel, R. & Spergel, D. N. 2001, *ApJ*, 556, 181
Heinze, A. N., Tonry, J. L., Denneau, L., *et al.* 2018, *AJ*, 156, 241
Jayasinghe, T., Kochanek, C. S., Stanek, K. Z., *et al.* 2018, *MNRAS*, 477, 3145
Levine, E. S., Blitz, L., & Heiles, C. 2006, *ApJ*, 643, 881
López-Corredoira, M., Cabrera-Lavers, A., Garzón, F., *et al.* 2002, *A&A*, 394, 883
Poggio, E., Drimmel, R., Lattanzi, M. G., *et al.* 2018, *MNRAS*, 481, L21
Ripepi, V., Molinaro, R., Musella, I., *et al.* 2019, *A&A*, 625, A14
Romero-Gómez, M., Mateu, C., Aguilar, L., *et al.* 2019, *A&A*, 627, A150
Shen, J. & Sellwood, J. A. 2006, *MNRAS*, 370, 2
Skowron, D. M., Skowron, J., Mróz, P., *et al.* 2019, *Science*, 365, 478
Wang, S., Chen, X., de Grijs, R., *et al.* 2018, *ApJ*, 852, 78
Wang, S. & Chen, X. 2019, *ApJ*, 877, 116

https://doi.org/10.1017/S174392131900869X Published online by Cambridge University Press