The evolution of the Galactic Warp

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Abstract: We review some of the traits of the Galactic disc and elaborate on the Milky Way's Warp, the recent studies investigating it, and its importance. We focus on the effect of this distortion on different age populations using a broad sample of young objects made up by Cepheids, masers, and HII regions. We attempt a fit on this sample and compare it to other populations models available in the literature. We find less agreement with the similar age population OB model than expected, although some general trends are shared among all the models plotted. We also compare the positions of objects in our sample with respect to a HI Model, but find no evidence regarding a warping trend with age.

I. INTRODUCTION

The Milky Way is a barred spiral galaxy with a stellar disc and a thin disc of stars of all ages, gas and other interstellar matter forming the spiral pattern of four arms and a central bar. The disc is populated by old and evolved stars, as well as younger objects, such as HII regions, OB associations and open clusters, whereas a rather spherical halo around the center contains older objects, including globular clusters, but little interstellar matter [1].

The Warp

One of the tell-tale features of the dynamical history of the Milky Way, one that has been observed in many other galaxies [2], is the fact that the disc is not a perfectly flat surface. It shows a certain distortion toward the edges that would give it an arched shape resembling an "S" when viewed edge-on, and this is known as the Galactic Warp. It has been noticed since the late 1950s, when observations of the galaxy of the 21-cm hydrogen line begun, hence becoming the focus of many studies [3][4][5]. Some of these studies have shown that the warping can be observed not only in neutral gas [6] but on stars, like red giants or Cepheids [7][8][9][11], as well as dust [13], often providing a series of parameters to describe them.

Regarding the origin of the Warp, some theories have already been explored [14]. For instance, this distortion could be caused by a misalignment between the disc rotation axis and the normal of the disc [15], resulting in a superposition of ingoing and outgoing waves that create a net normal oscillation of the disc. For these bending modes to be sustained in time several conditions must be met, and together with the effects on the halo that this mechanism would cause even in some of those cases, they add up to a number of constraints that some argue would make this theory less likely than others [14][16][17][18]. Another possibility is that infalling material with angular momentum misaligned with the rotation axis could have caused the warping. Some simulations [7] have shown that such an event could indeed account for the observed shape, and studies about the likelihood of an infall also support the theory as a plausible explanation [19]. Yet another hypothesis points at the Warp as a response of the disc to the tidal effects of some satellite, most likely one of the Magellanic Clouds or the dwarf galaxy Sagittarius [20], which orbits around our own.

Whatever the theory that agrees best with evidence, we can see how the Warp is a promising source of information about the past and present evolution of the Milky way and its possible interactions with other objects in its vicinity [22]. Moreover, these conclusions could become a foundation stone in the study of plenty of other galaxies undergoing similar phenomena.

The stellar Warp

Accurately describing the Warp is a task that requires access to a significant amount of accurate data: the location of enough Galactic objects to cover as much of the surface of the disc as possible. It is worth remembering that this is particularly difficult for the objects located across the Galactic center from us, since their light has to cross thousands of parsecs of dust and larger objects before reaching us. Furthermore, it is not enough that their light can be detected, their actual distances have to be computed accurately in order to determine their position in the Galaxy. Even space-based observatories operating in the infrared cannot completely escape such problems and inevitably have a limited reach. This means that even though the Warp's existence has been well known for years, finding an accurate model to describe it as a whole has been an impossible task to tackle until very recently, with the arrival of more advanced and thorough surveys and projects such as the Wide-field Infrared Survey Explorer (WISE), the "VISTA Variables in the Via Lactea" (VVV), the Optical Gravitational Lensing Experiment (OGLE) or Gaia, amongst others [3].

In fact, none of the models suggested so far have achieved excellent agreement with the data available. Sources available to the scientific community keep growing, offering better chances to obtain answers to questions such as those mentioned before. In the meantime, some general notions about the Warp that have been noted are: (1) it is negligible or non-existent for small radii, maybe up to a Galactic radius near the Sun's (R $\sim$ 8 kpc) and stretches out from there to the very end of the disc (R $\sim$ 20 kpc), (2) it has a positive side, with mean vertical distances to the Galactic plane $z > 0$, and

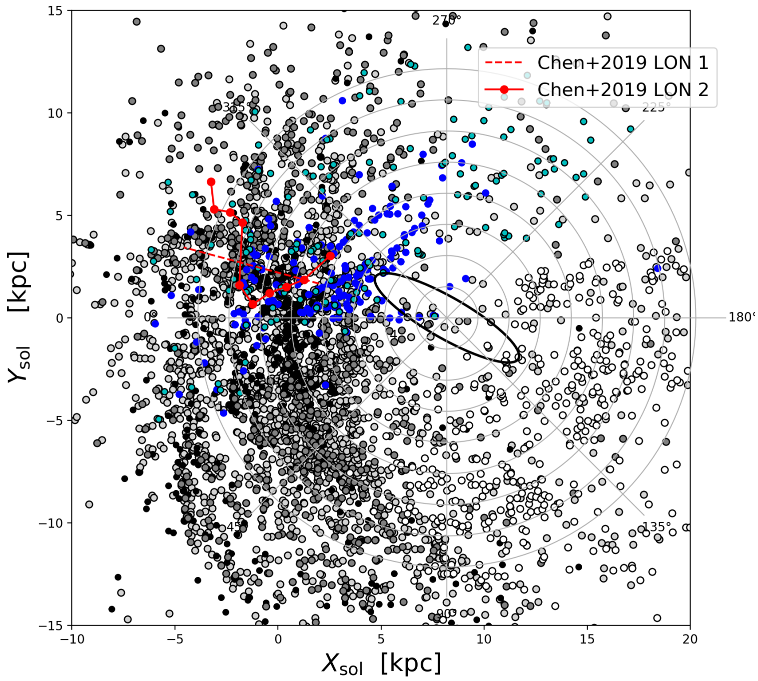

FIG. 1: The sample used in this work, plotted in cartesian Galactic coordinates and with sources distinguished by color: OGLE Cepheids [9] are light grey dots, Gaia DR2 Cepheids [26] are black, WISE Cepheids [8] are dark grey, VVV Cepheids [29] are white, masers [25] are blue, and HII regions [27] are cyan dots. The red lines and dots mark the line of nodes according to [8]

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a negative side, with distances $z < 0$, so that a "line of nodes" can be defined on the disc as the zero vertical displacement line separating the two [8], (3) it is probably different in shape for different age populations [11][24], and (4) it is most likely an evolving phenomenon [22].

No definitive conclusion about the difference of the warping with population age has yet been reached either, but it remains an important matter to discuss, since it is differences in space distributions of different age populations that tell us about *changes* in the general structure of the Milky Way. In the following sections we will address this question of whether different age populations are affected differently by the distortion of the galactic disc we call the Warp, giving some information about our data in section II, explaining the analysis applied and discussing the results in section III, and providing some conclusions in section IV.

II. DATA

In this work we have gathered data from several studies: (1) positions of molecular masers from Reid et al. 2019 [25], with measurements from the BeSSeL Survey using the Very Long Baseline Interferometry and the VERA project (both measuring in radio wavelengths that suffer little or no extinction as they cross the Galaxy), (2) positions of multiple HII regions gathered by Wenger et al. 2019 [27] using the WISE Catalog of Galactic HII Regions and the National Radio Astronomy Observatory Karl G. Jansky Very Large Array, (3) Cepheids from the VISTA Variables in the Via Láctea Survey (VVV) located in the southern hemisphere, censed and classified in Dekany 2019 [29], (4) WISE cepheids from Chen 2019 [8], (5) optical Cepheids from Ripepi 2018 (post-GaiaDR2) [26], and (6) Cepheids compiled from the variability surveys OGLE, ATLAS, and ASAS-SN by Skowron 2019 [9].

A possible first thought is that Cepheids make up most of our sample. There is a simple reason behind it: Cepheids, and in particular classical Cepheids, are supergiant variable stars whose period is related to their intrinsic luminosity, and its difference with the apparent luminosity (provided the convenient extinction data) can be used to compute their distance. Their period can also be related to age [28], which for classical Cepheids is relatively short, of up to 400Myr. These characteristics make them perfect candidates as tracers of the shape of the Galactic disc that they populate [29]. However, their distribution over the disc shows a connection with their age, a matter that we will discuss in section III.B.

III. ANALYSIS

We start by plotting the objects on the XY plane and also on RZ planes of different intervals of azimuth, so that we can check how well our sample covers the different regions of the disc and have a preliminary notion of the shape we are looking at.

This plot can be observed in Fig.1. We note that there are objects from our sample all over the disc, mainly concentrated in the near side of the Galactic disc.

A. Radial distribution and dependence on age

We repeated those plots labeling the age of the objects with a color scale. The age is obtained from the periods by using the calibration derived in Dekany 2019 [29] for several metallicities and extrapolating. The main feature arising from this map is visible more clearly in Fig. 2. We notice that towards the center more of the younger objects can be found and that the older population spreads farther from it and closer to the edges of the Galaxy. Before going any further, we have to ask ourselves whether this Cepheids distribution is reasonable:

- This may seem counter-intuitive, because our Galaxy undergoes an inside-out formation process [31][32], meaning that star-formation progressively reached the outer regions of the Galaxy over the past Gyr.
- In case this distribution is not authentic, but a consequence of an erroneous transformation to obtain age from period data, we try skipping the calibration and check how the periods are distributed. We encounter long periods towards the center and short ones toward the edges, which still implies the same age trend [28].
- We find that when carrying out a series of simulations using the Besançon Galaxy Model (BGM) [33][34], the resulting gas density justifies our distribution (see Fig. 2), that seems to be just a consequence of the higher star-formation rate in the Inner disc. The SFR is proportional to density$^{1.5}$[35], and given that gas density increases towards the center of the Milky Way, it is understandable that we find bigger mass, longer period Cepheids there.
- Moreover, we find that Cepheid distribution in [9] is quite similar to the one obtained here (see Fig. 3 in [9]). Those authors offer an alternative justification where the Cepheids reach the observed distribution as a consequence of three star formation bursts that they try to trace back in time. This reasoning would be more difficult to apply effectively to our larger sample, however.

We could thus conclude that this age distribution is reasonable and in agreement with other studies, and compatible with the inside-out formation of the Galaxy.

B. The Warp

We compare the distribution of our sample with different models (See Fig.3 3): a model with HI [6], the model in [24] (with an analytic expression from Reylé et al 2009 but the parameters for the standard version of the Besançon Galaxy Model), the model suggested in [10] and finally the model in [11] calculated for different populations: here we use their obtained parameters for an OB stars sample. They all show a common general trend (negative for approximately $0 < \theta < 180^o$, positive for $180^o < \theta < 360^o$) although their mutual deviations are high and intensified towards large radii.

We also explore how a fit would turn out for our young tracers. We use the analytic form of the model in [11] but with free parameters. It is important to take into account that this is only a preliminary fit. The parameters thus obtained define the model shown in Fig.3 as a red line.

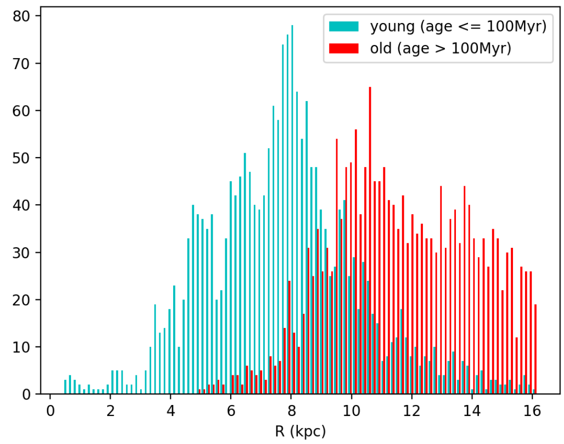

FIG. 2: Histogram of our sample's distribution with R. Sample divided into two age groups: young objects (age $\leq$ 100Myr, blue) and old objects (age over 100Myr, red). Simulations using the BGM [33][34] show that density of older Cepheids is expected to be dominating for galactic radii under $\sim$ 2.8 kpc and over $\sim$ 10kpc. We observe the last here, while in the inner region dust is too abundant to observe enough objects of any age.

We expected that, since our population and the OB sample in [11] have very similar ages (with OB stars only somewhat older in average than Cepheids), the obtained model would be very similar to theirs, however we find considerable deviations for these two models as well. Moreover, the fit obtained deviates significantly from our own sample for large radii in almost every azimuth bin, and in some regions even for intermediate radii (see for instance azimuths $180^o < \theta < 270^o$).

When we attempted a separate fit for two age groups in our sample (dividing it in a group with objects of age $\leq$ 100 Myr and another with tracers older than 100 Myr) we found that the model adjusted to the young group was completely unreliable: the parameters acquire values not only unphysical but with excessively large standard deviations associated. We suspect that the density law dependence on age in our Galaxy (that we discussed in the previous section) is responsible for this: it is very difficult to model the shape of the warp, that is only subtle for small radii, with a sample mostly distributed near the center of the Galaxy.

In order to find more conclusive evidence, we need to make comparisons taking into account the specific position where each object lies. Therefore, we try plotting the discrepancies between the distance to the disc of every Cepheid, maser or HII region in our sample and the mean value for HI at that position according to [6]. We choose neutral gas as a reference because this warping is more established and well measured phenomenon [12] than that of stars.

We can see the result in Fig.4. Every object is labelled with a color that represents its age. We observe again the earlier mentioned age gradient towards the edges. Some bins show increasing deviations towards the outermost radii (azimuths 0 to 90, 150 to 180 and 270 to 360),

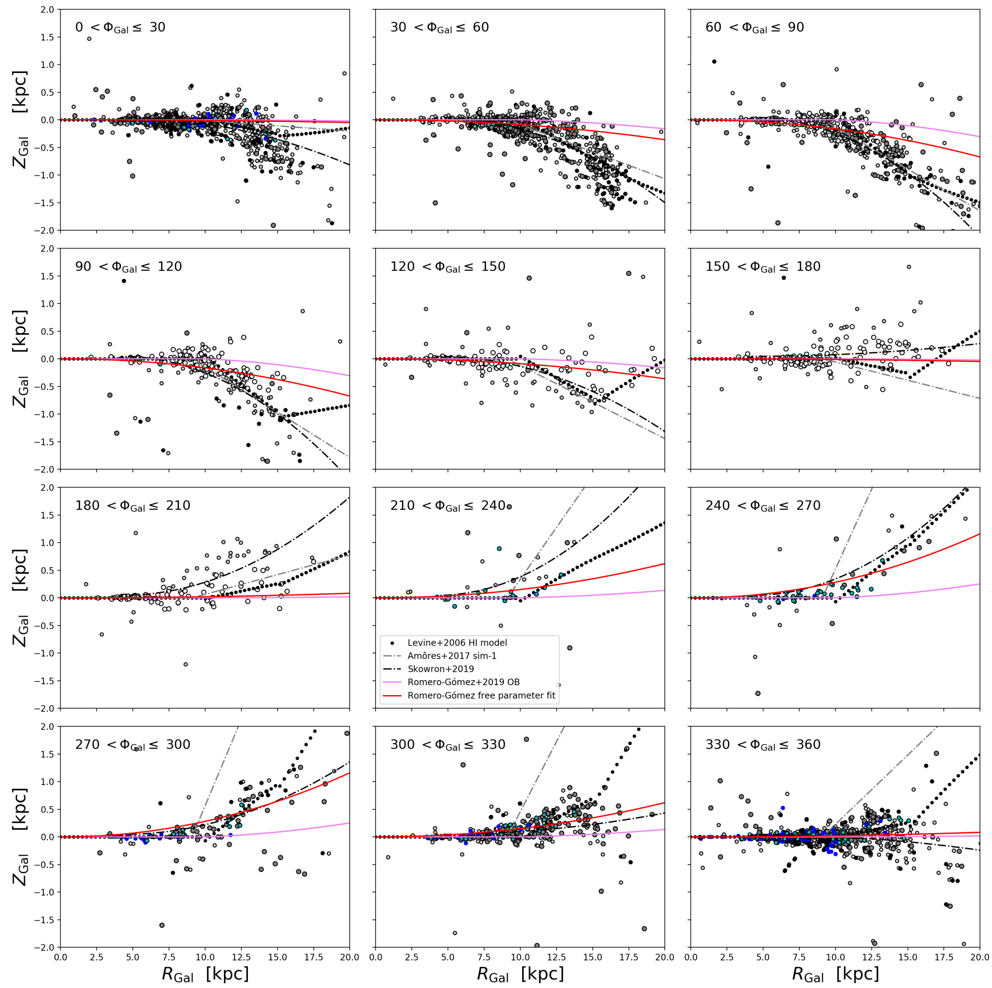

FIG. 3: Sample used in this work (color-code maintained from figure 1) plotted in azimuth bins together with some warp models available: HI model [6] in a black dotted line, a model using 2MASS data and a synthetic population using the Beçanson Galactic Model [24] in a grey dashed line, and a model for OB stars [11] in pink. Finally, the model derived here for Cepheids using the expression in [11], in red.

although the also increasing flaring makes it difficult to tell. Some other cells show rather uniform deviations along R, but this could have happened either because the trend really does not exist or because the population in those cells is too small to observe it.

IV. CONCLUSIONS

We use a sample made up of masers, HII regions (both considered young, and classical Cepheids with different ages up to a few Myr that we calculate following the method described in [9] and [29]). When we perform a plot by age, we make sure it agrees with evidence that proves the inside-out formation process in our Galaxy. At first glance it seems like it contradicts that evidence, but the density law for both populations as calculated by BGM models agrees with our distribution. More old stars than young stars should be found towards the center but the Galactic radii where they are expected to dominate is clouded by dust and extinction, since little can be observed in that area.

A separate fit for each age group in our sample is attempted, but our sample has too few young tracers for the outermost radii and the result is incongruous. A free parameter fit applied to the whole sample gives better results (always in qualitative terms), and we are able to compare a model of our sample with others from the literature. The model obtained here is more similar to the OB model than the others, but we expected more agreement given the similarity in age from both samples. One possible explanation is the presence of contaminants in the OB sample selection. Furthermore, we should not forget that both samples considered are susceptible to sources of error that are very difficult to avoid, such as patchy interstellar extinction or sky-dependent parallax errors, resulting in possible distance biases.

Finally, the comparison between vertical distances in our sample and the corresponding to the HI model [6] is little conclusive: there is increasing flaring towards larger galactic radii but it is difficult to see an actual trend. As a result, we find that no quantitative conclusions can yet be drawn from our comparisons regarding difference in warping with population age.

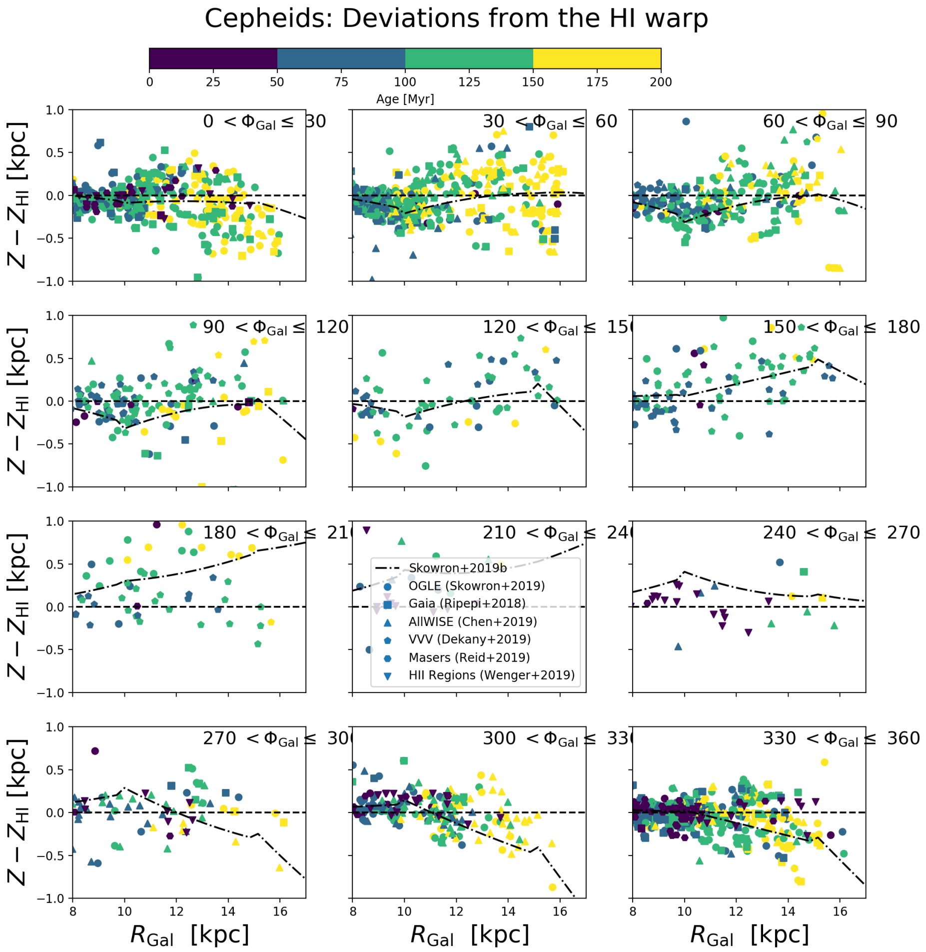

FIG. 4: Vertical deviation of the objects in our sample from the HI warp [6] at their position. The objects are color-coded by age. We observe here again the radial distribution discussed in III.B

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